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A Strain-Life Module for CGAP: Theory, User Guide and Examples

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ABSTRACT

Existing airworthiness standards require that all aspects of fatigue be considered in the design, development and maintenance of aircraft structures. To minimise costs and improve combat readiness requires accurate and efficient fatigue life evaluation. This report details the introduction of a strain-life algorithm known as FAMSH into the software tool suite known as CGAP developed and maintained at the DSTO. Along with improvements to the original FAMSH code this most recent development introduces a materials database and dynamic memory allocation. With other additional improvements the latest release of the CGAP environment seeks to improve the ease with which the engineer is able to accurately and reliably conduct fatigue life analysis. Contained within this report is an explanation of the strain-life theory in conjunction with a detailed description of its implementation in the CGAP GUI environment. Examples are provided to guide the user through its operation.

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Executive Summary

The assessment of fatigue damage in structures is an essential and an integral part of the management of air vehicles within the Australian Defence Force (ADF). The ADF Australian Air Publication 7001.053 states "... to assure structural airworthiness, management of Aircraft Structural Integrity (ASI) is essential from the acquisition stage, when the specification is developed, through to fleet retirement." As such, the aircraft certification process requires that fatigue damage be assessed and critical areas, susceptible to fatigue damage, identified. This highlights the importance of methods to evaluate fatigue damage to the overall safe and economical management of aircraft. Hence the need for robust user friendly software which the engineer can use to assess the fatigue life of critical structural elements.

Improvements in these methods and tools can be achieved in several ways, for example, by providing consistent material data, the use of built-in error checking, and the use of a familiar graphical user interface. This document discusses the incorporation of a strain-life methodology into an existing software tool CGAP. A detailed description of the strain-life theory and how it has been implemented into the CGAP environment is provided. The document also provides a thorough explanation of the operation of the software tool. Finally a step by step problem is worked through for the users benefit.

Accurate fatigue life assessment and life extension of metallic aircraft structures directly benefits defence. These benefits through improvements in prediction reliability can be realised in terms of reduced operational and maintenance costs, improved performance and combat readiness.

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Abbreviations

AAP	Australian Air Publication
ADF	Australian Defence Force
ASI	Aircraft Structural Integrity
CGAP	Crack Growth Analysis Program
CI	Crack Initiation
DBI SST	DataBase Interface Spectra Sequencing
DGTA	Director General of the Technical Airworthiness
DSA	Damage Source Assignment
DSN	Defence Support Network
DSTO	Defence Science and Technology Organisation
FAMS	Fatigue Analysis of Metallic Structures
FAMSH	Fatigue Analysis of Metallic Structures Hu
GUI	Graphical User Interface
NDT	Non Destructive Testing
OEM	Original Equipment Manufacturer
SLAP	Structural Life Assessment Program
SMP	Structural Management Plan
SPO	System Program Office
TP	Turning Point
TPP	Turning Point Pair

1. Introduction

The assessment and assurance of fatigue damage predictions in structures is an essential part of the management of air vehicles within the Australian Defence Force. The AAP 7001.053 [1] states that “to assure structural airworthiness, management of Aircraft Structural Integrity (ASI) is essential from the acquisition stage, when the specification is developed, through to fleet retirement.” The through-life support of aircraft necessitates the assessment of fatigue damage caused by service loads and its effects on structural airworthiness. As such methods of fatigue evaluation are important in the overall safe and economical management of aircraft. In practice the analytical assessment of fatigue damage, substantiated by coupon, component and full-scale tests, form the basis of technical data for the design of airworthiness structural integrity management plans. Given that accurate fatigue life assessment is critical to the safe and economical through-life support of aircraft, it is important that we develop algorithms and tools that are intuitive and user-friendly to support the structural engineer in the process of quality assurance.

The total fatigue life of a structure may be assessed by using one of four approaches: (1) by assuming the total fatigue life of a structure is governed entirely by crack initiation; (2) by assuming that the total fatigue life is governed entirely by crack growth; (3) by treating the total fatigue life of a structure as a serial combination of crack initiation and crack growth; and finally (4) by a parallel application¹ of both crack initiation and crack growth analyses. The first approach was typically used in the early years of fatigue assessment and is still the design practice of some industries where no regular inspections of the structures are carried out. The second approach, which is an emerging method, relies on the accurate prediction of the growth of very small cracks that takes place in the early stages of fatigue damage. With the gradual improvement in short crack growth theory, this approach may gain more prominence. The serial combination approach, which has been adopted for the P-3C fleet assessment [2], treats the early stages of fatigue damage as a process of crack initiation and then treats the subsequent fatigue damage in terms of crack growth². The fourth approach is being used on some later generation combat aircraft, particularly where low structural maintenance must be assured.

Different fatigue crack initiation models are routinely used in the safe-life design and the development of aircraft structural integrity management plans. One of the most commonly used fatigue crack initiation models is the so-called strain-life method. The theory that underpins the strain-life method forms the basis of the fatigue-life tool FAMS [3, 4] and FAMSH. FAMSH is a modified version of FAMS with additional expanded functionality with fewer limitations imposed. However, both FAMS and FAMSH lack an intuitive user interface and a method by which to manage material properties. Recently the FAMSH source code has been incorporated as a module into the Windows GUI known as CGAP. CGAP provides a common user friendly utility that can be used to control the material property definitions

¹ The particulars of the combination account for the limitations of each model assessed against part inspectability; damage susceptibility; NDI capability; criticality of the structure; new aircraft materials; and cost to repair/replace

² The crack initiation and growth stages are delineated by a crack size relating to the capability of non-destructive inspection technique and the limitations of the crack growth models.

which are important in achieving consistency in input data that underpins the advice provided to the ADF. The introduction of error checking, consistent material database and intuitive interface will ultimately minimise mistakes and improve the accuracy and assuredness of advice.

The aims of this document are to

- summarise the salient points of the strain-life theory;
- explain how the strain-life approach has been implemented in CGAP;
- provide guidance for the new module;
- provide examples demonstrating the use of the new module.

Accurate fatigue life assessment and life extension of metallic aircraft structures directly benefits defence. These benefits can be realised in terms of reduced operational and maintenance costs, improved performance and combat readiness. Improvements in these methods and tools can be achieved in several ways, for example, by providing consistent material data, built-in error checking, and a familiar graphical user interface (GUI). All these and others will lead to improved robustness in predictions which ultimately contributes to the more efficient and reliable management of ASI fatigue advice.

The advice, guidance and developments contained in this report contribute directly and/or indirectly to the following important high level issues:

1. Quality assurance is an integral part of ASI management
2. A wide range of design philosophies, ASI management philosophies, fatigue models, material types and analysis options must be addressed to support ADF aircraft, both in-being and in-acquisition.
3. Australian defence aircraft are sustained by multiple partners, namely the individual OEMs and the Australian Defence Support Network (DSN)³
4. A common, flexible and transparent fatigue prediction tool set is required to assure all of the above can be supported.

2. CGAP: Crack Growth Analysis Program

CGAP is a DSTO developed software tool that contains a set of algorithms commonly used to assess and analyse fatigue damage. It is envisaged that CGAP will gradually become a one-stop tool set with which the engineers can perform most of their required fatigue analyses. CGAP is a Microsoft Windows-based application with a GUI and an integrated database for the management of material properties, geometry sets and load cases. The GUI assists the user in entering input data, inspecting spectra and checking for data consistency. It also provides a simple plotting capability for crack growth outputs. CGAP contains a native crack growth analysis module based on the concept of plasticity-induced crack closure. In addition to all the functionalities of FASTRAN3.8[5], the native module also has the capability for crack growth analysis involving notch plasticity, and probabilistic crack growth analysis based on the

³ The DSN comprises ASI-DGTA, DSTO, SPOs and numerous Australian industry partners

Monte Carlo method. For probabilistic analysis, the initial crack size, crack growth rate parameters and the peak spectrum stress can be randomised using three distribution functions. Importantly, CGAP interfaces seamlessly with FASTRAN3.8[5] and the DKEFF[5] code. A recent update to the program includes the incorporation of the FAMSH code described in this report. The inclusion of FAMSH to the CGAP environment expands the functionality of CGAP to include a strain-life approach for crack initiation analysis.

3. FAMSH: Strain Life Algorithm

FAMSH is a software tool based on FAMS [3, 4] and developed at the DSTO. It is used to perform fatigue life calculations based on a strain-life methodology. FAMSH was originally developed to support the technical interpretation and development of the structural management plan (SMP) for the P-3C. It is currently being used in the certification process of the C-130J. FAMSH is based on FAMS [3, 4], with several added equivalent strain equations, new outputs for damage analysis and support for the DBI/SST spectrum format [6]. The current release of FAMSH provides fully dynamic memory management to allow the program to be used on spectra of any size, only limited by the size of the physical memory of the hardware, without recompilation. Furthermore, the same FAMSH source code is now used to generate the executable file on both Windows and Linux platforms, thus ensuring the consistency and currency of the results obtained from the code.

4. The Strain-Life Approach

Traditionally, most theories on fatigue relate the damage caused by cyclic loading to the local stress or strain ranges, resulting in two similar but different approaches: stress-life approach and strain-life approach. The stress-life approach is commonly used for low loads and high cycle fatigue when local plasticity is negligible, while the strain-life approach is commonly used in situations where local plasticity may occur. For the stress-life approach, the main material data required is the stress-life curve for the stress concentrator concerned. Thus different stress-life data need to be generated for different notch features. The local stresses and strains are calculated using the stress concentration factor of the notch feature. For the strain-life approach, it is assumed that as far as fatigue damage is concerned the material at the notch root behaves like as a smooth (un-notched) specimen. Thus, only one set of strain-life data obtained from a smooth specimen is required for the basic material data. However, validation against other notched data is usually required for ASI purposes. When local plastic deformation occurs, the local stresses and strains are calculated using a method such as Neuber's equation. When the applied stress is low, the local stress will simply be a product of the applied stress and the elastic stress concentration factor. Therefore, theoretically, for low stress and high cycle fatigue, the strain-life approach is identical to the stress-life approach. Hence the strain-life approach may be considered a more general approach for modelling fatigue damage.

The block diagram in Figure 1 illustrates the process of the strain-life approach. The basic input data are the stress concentration representing the geometry of the specimen, the cyclic

stress-strain relation, the strain-life relation of the material, and the applied load sequence. The load sequence, the stress concentration factor, the stress-strain relationship and the Neuber's rule are used to determine the local stress and strain history. The local stress history is then processed using the Rainflow counting method to form pairs of peak and valley stresses (or stress cycles) that relates to fatigue damage. The counted stress cycles are converted to strain cycles which are in turn converted to equivalent fully-reversed strain cycles, based on the selected equivalent strain equation. Finally, the converted equivalent strain amplitude is used to determine the number of cycles the material would have endured under this strain amplitude to cause failure. The inverse of this number gives the fatigue damage attributable to this strain cycle. By summing up the damages caused by all the Rainflow-counted strain cycles, the total damage by the spectrum is obtained. The inverse of the total damage gives the fatigue life in terms of the number of passes of the spectrum. It should be noted that this approach does not account for the history effect of the load sequence. It uses the Miner linear summation rule. The details of the main blocks in Figure 1 are discussed in the following sections.

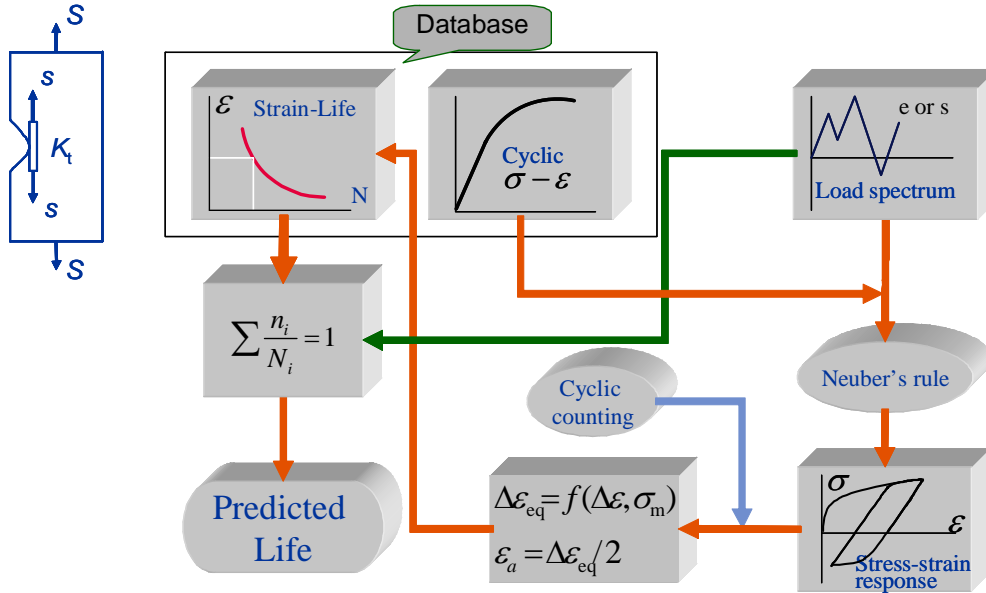


Figure 1: Block diagram illustrating the process of strain-life approach

From a continuum mechanics perspective, the strain-life approach empirically relates the local elastic-plastic behaviour of a material to fatigue damage. Thus understanding the elastic-plastic behaviour of the material is fundamental to the application of the strain-life approach. Given a cyclic load history, a methodology is required to accurately determine the stress and strain at the notch root. FAMSH uses the Neuber's method which will be discussed in the following section.

4.1 Notch Stresses and Strains

To apply the strain-life approach, a means to accurately determine the strain at the location of interest is required, usually the root of a notch on a structure. Due to stress concentrations that occur at such locations, local stresses may exceed the yield stress (or proportional limit) of the

material. Under such conditions, the local stresses and strains can no longer be determined using the stress concentration factor alone. A relationship such as Neuber's equation is needed to supplement the elastic equilibrium equations and the stress-strain relationships. This simple approach provides a relatively sound prediction of plastic response, and is suitable for dealing with fatigue loading. The discussions presented here are confined to plane stress and uniaxial stress only, which are the cases dealt with in FAMS and FAMSH.

4.1.1 Neuber's Method

Several methods exist that may be used to estimate the notch root stress and strain, but the most commonly used one is that by Neuber [7]. The strain-life module (FAMSH) in CGAP utilises the Neuber method for evaluating notch root stresses and strains.

For elastic deformation, the theoretical stress concentration factor K_t can be used to evaluate the local stress. According to the definition of K_t ,

$$K_t = \frac{\Delta\sigma}{\Delta S} = K_s, \quad (1)$$

where ΔS is the remote elastic stress range and K_s is the stress concentration factor. Similarly in the elastic regime we have

$$K_t = \frac{\Delta\varepsilon}{\Delta e} = K_e, \quad (2)$$

where Δe is the remote elastic strain range and K_e is the strain concentration factor. In the elastic regime both the stress concentration factor and the strain concentration factor are equal to the theoretical concentration factor, *i.e.* $K_t = K_s = K_e$.

Neuber noted that in the post yield range these relations would no longer hold. That is, the stress concentration factor K_s would decrease and the strain concentration factor K_e would increase relative to the elastic stress concentration factor K_t . Neuber hypothesised that the elastic stress concentration factor would be equal to the geometric mean of K_s and K_e . *i.e.*,

$$K_t^2 = K_s K_e. \quad (3)$$

Therefore using equation (1) and (2) equation (3) can be rewritten to give

$$\Delta\sigma\Delta\varepsilon = K_s\Delta SK_e\Delta e = K_t^2\Delta S\Delta e \quad (4)$$

As the remote stress is assumed to be within the elastic range we have $\Delta S = E\Delta e$, otherwise the whole cross-section will yield,. Therefore

$$\Delta\sigma\Delta\varepsilon = \frac{K_t^2\Delta S^2}{E}, \quad (5)$$

where E is the modulus of elasticity. This is Neuber's equation which relates the remote elastic stress range to the local elastic-plastic stress-strain range at the notch.

Figure 2 shows graphically how the Neuber rule is applied to the stress strain relationship. Neuber's rule for a case where $K_t = 1$ suggests that the product of the applied elastic stress and strain is equivalent to the product of the elastic-plastic stress and strain. Geometrically, this means that the area of A is assumed to be equal to the area of B.

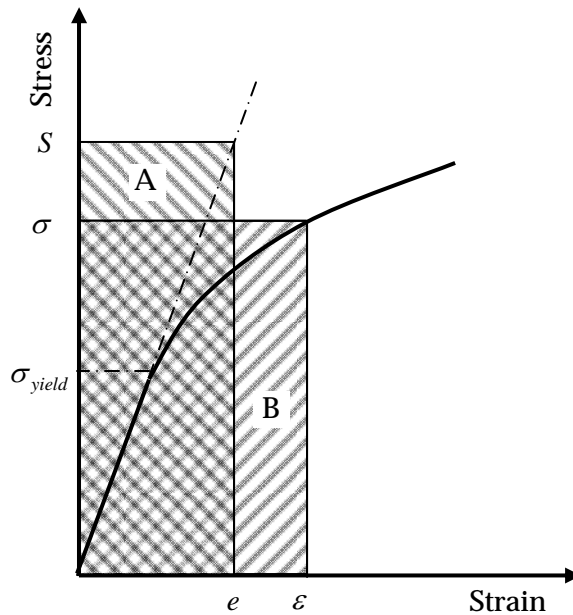


Figure 2: A graphical representation of the Neuber rule assuming a stress concentration factor of $K_t = 1$

4.1.2 FAMSH Representation of Stress-Strain

The stress-strain relationship in Figure 3 can be represented in various ways. The Ramberg-Osgood equation is commonly used to represent the monotonic stress-strain curve, but can also be used to fit the cyclic stress-strain data. In FAMSH, the cyclic stress-strain curve or hysteresis stress versus hysteresis strain curve (as opposed to the monotonic stress-strain curve) can be represented in one of two ways: either in tabular or equation format. In tabular format, the data may be cyclic stress versus cyclic strain, or hysteresis stress versus hysteresis strain. In equation format, parameters are used to represent the cyclic stress-strain curve. Further information on creating material definitions can be found in section 5.3.2. More detail on the origins of the FAMSH stress-strain relationship can be found in the Appendix A.

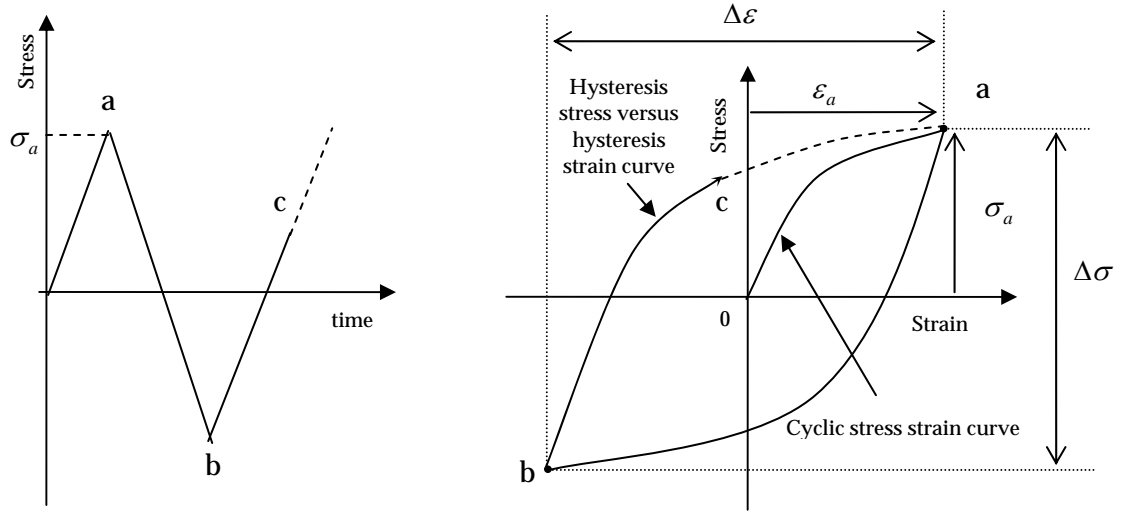


Figure 3: Stress-strain relationship after the application of a load σ_a and then followed by fully reversed loading

The hysteresis stress versus hysteresis strain curve is evaluated assuming Masing-type behaviour⁴ [8] and using the following relations:

$$\frac{\Delta\sigma}{2} = \sigma_a \quad (6)$$

$$\frac{\Delta\epsilon}{2} = \epsilon_a \quad (7)$$

Using the FAMSH stress-strain relationship in Appendix A and equations 6 and 7 we have

$$\begin{aligned} \frac{\Delta\epsilon}{2} &= \frac{\Delta\epsilon_e}{2} + \frac{\Delta\epsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{1}{K'} \left(\frac{\Delta\sigma}{2} - \sigma_{pl} \right) \right)^{\frac{1}{n'}}, \quad \sigma_a > \sigma_{pl} \\ \frac{\Delta\epsilon}{2} &= \frac{\Delta\sigma}{2E} \quad \sigma_a \leq \sigma_{pl} \end{aligned} \quad (8)$$

where $\Delta\epsilon_e$ and $\Delta\epsilon_p$ are the elastic and plastic components of the total strain range $\Delta\epsilon$ respectively, σ_{pl} is the proportional limit, σ_a is the total applied stress and K' and n' are the cyclic strength coefficient and cyclic strain hardening coefficients respectively. Equation 8 describes the form of the stabilised hysteresis loop representing the cyclic stress-strain behaviour.

4.1.3 Fatigue Notch Factor

The previous discussion of the strain-life method suggests that the fatigue life of a smooth (un-notched) specimen can predict the fatigue behaviour at the notch root of a notched

⁴ Masing-type behaviour assumes that the hysteresis loop is twice the cyclic stress-strain curve.

structure. Elastic theory can be used to relate the remote stress to the local stress at the root of a notch using the stress concentration factor K_t . In the case of fatigue it was originally hoped that this would hold true for the fatigue strength, the amplitude of the applied fully-reversed cyclic stress that will cause failure after a series of repeated cycles. However, it has been found that the ratio of the fatigue strengths of the un-notched and notched specimens (at the same number of cycles) is not equal to K_t . This is because in reality the notched fatigue strength is also affected by the notch radius, material strength, material properties, etc [9]. To correct this behaviour a new parameter, the fatigue notch factor K_f , was introduced to replace K_t .

The fatigue notch factor is not a theoretical parameter like the stress concentration factor and is not just a function of the geometry and remote loading. The fatigue notch factor relates the fatigue strength of a smooth specimen to that of a notched specimen using the following equation.

$$K_f = \frac{\text{Smooth fatigue strength}}{\text{Notched fatigue strength at equal life}} \quad (9)$$

If the notched fatigue strength was just a function of the geometry and the load then K_f would be equivalent to the elastic stress concentration factor. Thus the fatigue notch factor is essentially an empirical parameter used to account for these other factors.

An empirical relation was developed by Neuber to evaluate the fatigue notch factor. Neuber developed what is known as the Neuber notch factor based on the hypothesis that stresses may be assumed constant over small distances [9]. This factor is defined as:

$$K_N = 1 + \frac{K_t - 1}{1 + \sqrt{a/r}} \quad (10)$$

where a is the characteristic length dependant on the material and r is the notch radius. Some values for the characteristic length a can be found in [9]. The Neuber notch factor K_N is only appropriate for unloaded holes or notches in individual specimens. It does not take into account any effects the material itself might introduce. In FAMSH, the fatigue notch factor is used in place of the theoretical stress concentration factor to calculate the local stress and strain.

4.2 Stress and Strain Related to Fatigue Life

Unlike the stress-life approach the strain-life approach does not require test data for a variety of notch types. Rather, the strain-life methodology reduces the required input data by providing a more general means of estimating fatigue damage and by considering prior knowledge about stress-strain relationships (i.e. Neuber, K_f). This is achieved by assuming that the fatigue behaviour at the notch root is equivalent to that of uni-axial test specimens, see Figure 4. In other words the fatigue life of material at the root of a notch is equivalent to the fatigue life of an un-notched specimen of the same material subjected to the same cyclic straining.

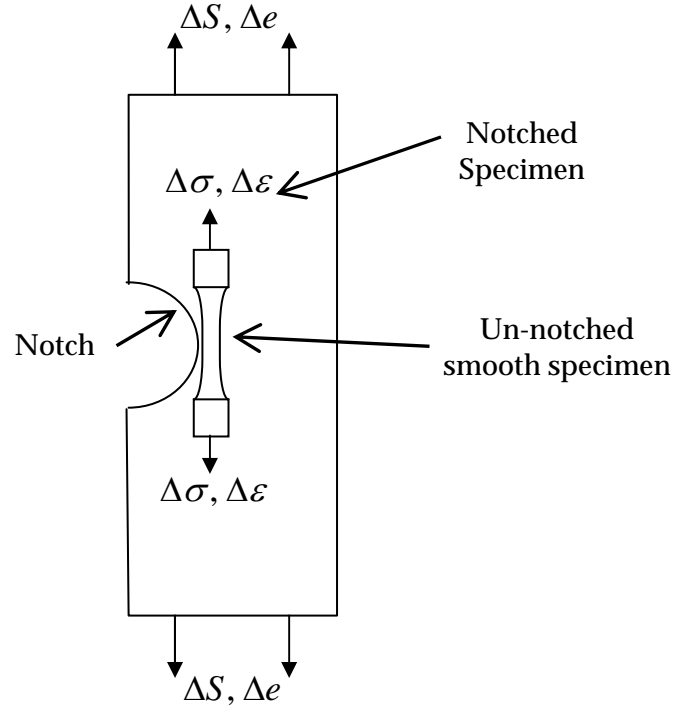


Figure 4: Diagram demonstrating the rationale for using strain-life data obtained on smooth specimens to predict the fatigue life of notched specimens

The basic fatigue life data needed for the strain-life approach are the fatigue lives at various strain amplitudes. These data are acquired by conducting tests on smooth cylindrical specimens subjected to fully-reversed constant amplitude loading under strain control. Similar to Basquin's observation on stress-life data [10], Coffin [11], and Manson [12] found that the plastic-strain-life data could be linearised on a log-log scale and be expressed as:

$$\frac{\Delta \varepsilon_{pl}}{2} = \varepsilon'_f (2N_f)^c, \quad (11)$$

where $\Delta \varepsilon_{pl}$ is the plastic strain range, ε'_f is the fatigue ductility coefficient, $2N_f$ is the number of reversals to failure and c is the ductility exponent. Combining the above with the Basquin equation the fatigue life may be related to the total strain range experienced by the material. In FAMSH, this relationship is described in the following form:

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\left(2^b \frac{\sigma'_f}{E}\right)}{N_f^{-b}} + \frac{\left(2^c \varepsilon'_f\right)}{N_f^{-c}} = \frac{\alpha}{N_f^{b'}} + \frac{\beta}{N_f^{c'}} \quad (12)$$

where the parameters α , β , b' and c' are related to the fatigue strength and ductility coefficients and exponents via:

$$\begin{aligned}
\alpha &= 2^b \frac{\sigma'_f}{E} \\
\beta &= 2^c \varepsilon'_f \\
b' &= -b \\
c' &= -c
\end{aligned} \tag{13}$$

For a particular material the strain-life (ε - N) data must first be obtained through a series of tests. These tests involve the application of fully-reversed loads under strain control to smooth un-notched specimens. Once the ε - N curve is known it is then possible to estimate the number of cycles to failure for a given strain history. It is useful to recall that the ε - N diagram deals with strain amplitude and as such the total strain amplitude is the sum of the elastic and plastic components. Figure 5 shows the total strain behaviour in terms of the number of reversals to failure for 4340 steel [13]. The elastic and plastic components of equation 12 have been plotted in Figure 6 and the linear relationship with fatigue life is evident. Similar relationships have been observed in many metals.

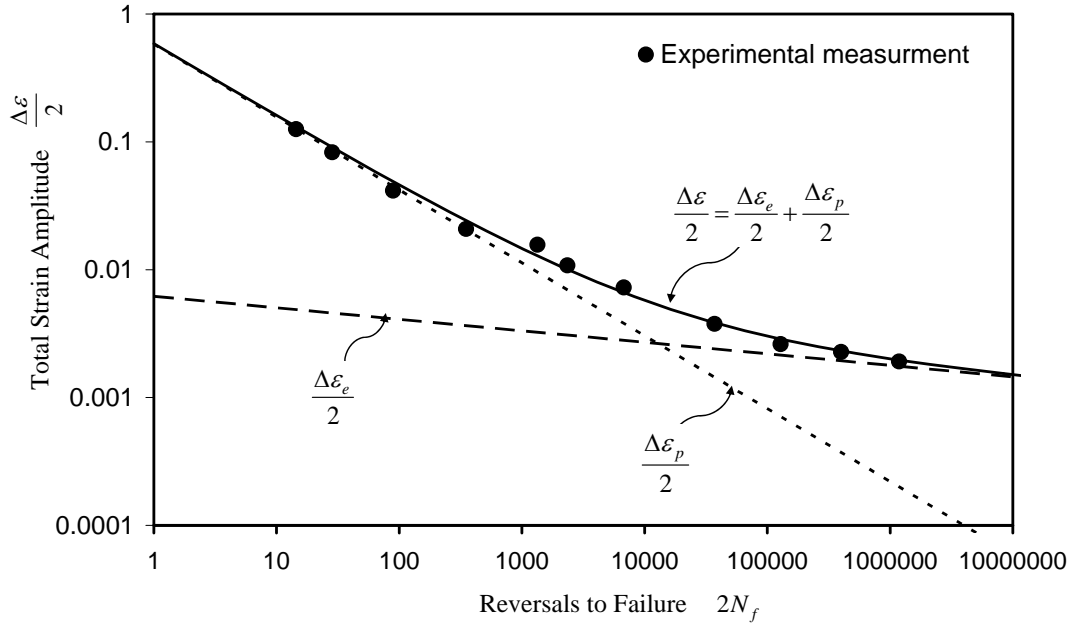


Figure 5: Low-cycle fatigue behaviour of annealed 4340 steel showing the total strain amplitude for constant strain amplitude loading[13]

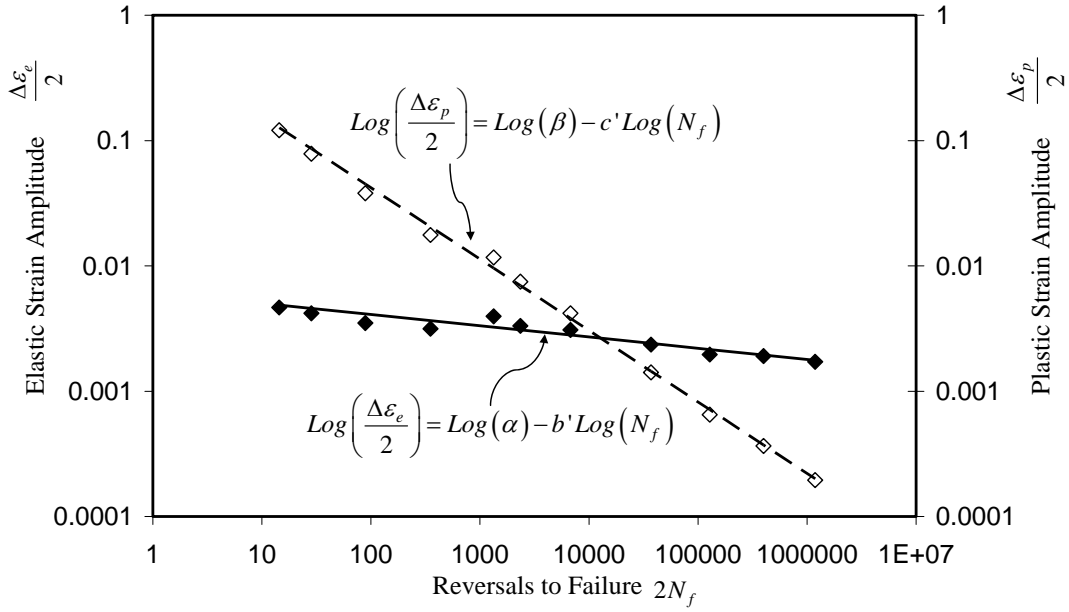


Figure 6: Low-cycle fatigue behaviour of annealed 4340 steel showing the elastic and plastic components of strain amplitude for constant strain amplitude loading[13]

4.3 FAMSH Representation of the Strain-Life Curve

FAMS and FAMSH allow a more flexible representation of the strain-life curve based on equation 12. It is also worth noting that FAMSH also supports tabulated data to represent the strain-life curve. While the codes allow the user to implement equation 12, a more accurate representation of the strain-life relationship over the whole strain range can be achieved by piece-wise fitting equation 14 to experimental data. This process is depicted in Figure 7. The strain-life data are divided into three segments, dominated by plastic strain, elastic strain or by a balanced combination of elastic and plastic strain. Here the elastic component of strain can be represented with

$$\frac{\Delta \varepsilon_e}{2} = \frac{\alpha}{N_f^{b'}} = \frac{C1}{N_f^{B1}} \quad \text{or} \quad \frac{C3}{N_f^{B2}}, \quad (14)$$

and the plastic component can be represented with

$$\frac{\Delta \varepsilon_p}{2} = \frac{\beta}{N_f^{c'}} = \frac{C2}{N_f^{G1}} \quad \text{or} \quad \frac{C4}{N_f^{G2}}. \quad (15)$$

In Figure 7 ELET and PLET are strain ranges chosen to define the transitions between regions 1, 2 and 3. Depending on the values of ELET and PLET, different combinations of equations are used to represent the entire strain-life curve, as detailed in Table 1. The constants used in Table 1 and Figure 7 can be found by curve-fitting equation 12 to experimental data. See Appendix B for an example of determining the input parameters for the FAMSH strain-life equation.

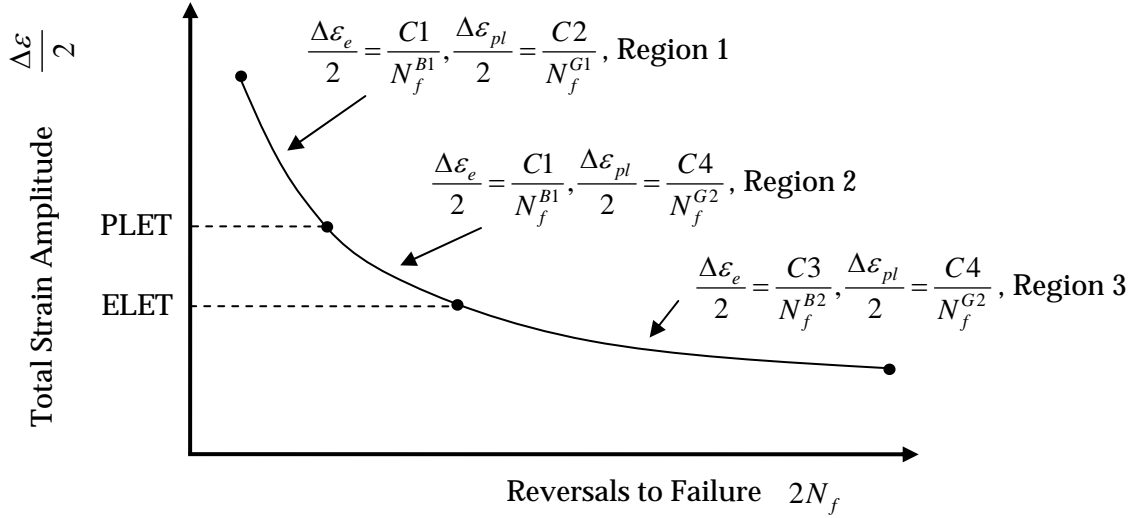


Figure 7: Strain-life curve representation in FAMS and FAMSH

Table 1: Parameters used in FAMSH to defined each region of the strain-life curve in Figure 7

	Total strain $\Delta\epsilon_a$		
	Region 1	Region 2	Region 3
PLET=ELET=0	$f(C_1, B_1, C_2, G_1)$	N/A	N/A
ELET>PLET=0	$f(C_1, B_1, C_2, G_1)$	$f(C_3, B_2, C_2, G_1)$	N/A
PLET>ELET=0	$f(C_1, B_1, C_2, G_1)$	$f(C_1, B_1, C_4, G_2)$	N/A
ELET>PLET>0	$f(C_1, B_1, C_2, G_1)$	$f(C_3, B_2, C_2, G_1)$	$f(C_3, B_2, C_4, G_2)$
PLET>ELET>0	$f(C_1, B_1, C_2, G_1)$	$f(C_1, B_1, C_4, G_2)$	$f(C_3, B_2, C_4, G_2)$

4.4 Rainflow Counting

Rainflow counting is an internal function that is conducted by the FAMSH code. It is performed on the local stress history derived from the applied load spectrum using the Neuber rule. The load history is input into FAMSH as a series of turning points. The strain-life algorithm used in FAMSH requires that this spectrum be Rainflow counted. Rainflow counting has a physical basis and that is when metals are subjected to repeated loading the stress-strain response forms hysteresis loops like those in Figure 8. If the loading remains in the elastic regime then the hysteresis loops remain closed such as that produced by the cycle G to H. If the loads applied are large enough to cause plastic yielding then open hysteresis loops are formed. It is useful to note that if the loading does not cause plasticity, then any hysteresis loops formed degenerate to a straight line. Any actual loop, with non-zero enclosed area, indicates plasticity. The area contained by the hysteresis loops represents the energy lost during that cycle. In the case of a variable amplitude load sequence, hysteresis loops can be drawn such that one finds small loops contained within larger loops. The Rainflow counting scheme developed by Matsuishi and Endo [14] may be used to extract the peak and valley of all the closed hysteresis loops from a complex spectrum. It is based on the observed memory effect in many metals where a smaller load cycle appears to contribute an interruption to a larger load cycle. In Figure 8 the load cycle B-C serves as a small interruption to the larger

load cycle A–D. At point C as the load increases back to B the stress-strain curve resumes its original path from A to D in effect remembering the previous load application from A to B.

The Rainflow counting method can be envisaged by rotating the strain-time history so that the vertical axis is the time and the horizontal axis the strain amplitude. The strain history can be viewed as a series of sloping roofs that overlap one another at different points. The Rainflow cycles are then defined by the manner in which rain is allowed to drip down the roofs. A number of rules are used to define the behaviour of the rain.

The process of Rainflow counting is as follows [14] :

- Allow the rain to start from the largest peak (or valley) and run down the roof till it falls off completely.
- Start the next droplet of water from the valley (or peak) at the point where the droplet fell from the roof and allow it to run in the opposite direction till it falls off the roof. This constitutes one Rainflow counted cycle.
- Next begin again from the first load reversal that has not been fully touched by a droplet. Allow the droplet to run till it falls off and terminate this path when either it falls off completely or hits a previous path created by a previous droplet.
- From this reversal, allow a droplet to flow in the opposite direction and terminate in a similar manner. This now becomes the next Rainflow counted cycle. Continue the process until all the cycles within the load spectra have been counted.

In Figure 8 there are 4 full Rainflow cycles A–D, B–C, E–F and G–H which correspond to the 4 closed stress-strain hysteresis loops. For further information refer to Fuchs, Fatemi and Stephens [15] or Ellyin [16].

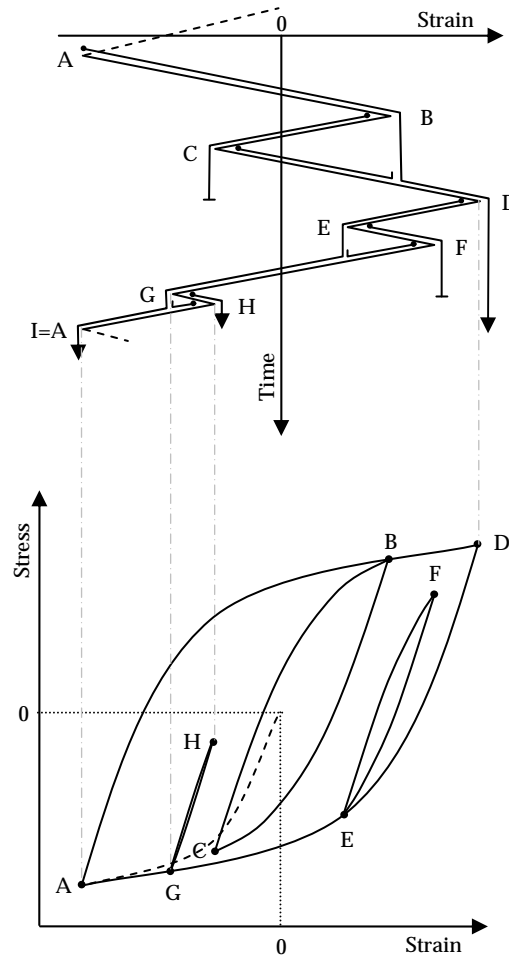


Figure 8: Pictorial Representation of the Rainflow Counting Method

4.5 Mean Stress Effects and Equivalent Strain Equations

For fully reversed strain cycles (i.e. $R = \text{minimum stress}/\text{maximum stress} = -1$) the strain range can be directly used to obtain the corresponding fatigue life from the ε - N curve. For a variable load history, the strain cycles are usually not fully reversed, hence it is important to account for the effect of (non-zero) mean stresses on fatigue life. An equation that converts a general strain cycle ε_a where $R \neq -1$ into an equivalent cycle ε_{eq} where $R = -1$ is known as an equivalent strain equation, and several models have been developed over the years.

In general Dowling [17, 18] provides some guidance to the use of equivalent strain equations. He concludes the following:

- The Morrow equation is reasonably accurate in most cases when the true fracture strength is known.
- The Smith Watson and Topper equation provides good results in most cases and for aluminium alloys produces somewhat more accurate results when compared to the Morrow equation.
- In cases where there is enough data to determine the exponent m in the Walker equation, the Walker equation gives superior results.
- For high strength aluminium alloys the exponent m in the Walker equation is approximately 0.5 reducing the Walker equation back to the Smith Watson Topper equation. For lower strength aluminium alloys the exponent is higher.

FAMSH implements the following eight equivalent strain equations:

i) Modified Morrow equation [19]

$$\varepsilon_{eq} = \frac{\varepsilon_a}{1 - \frac{\sigma_{mean}}{\sigma_F}} \quad (16)$$

where σ_{mean} is the mean stress and σ_F is the true fracture strength⁵, the engineering stress at the beginning of fracture during a tensile test.

ii) Loopin equation [20]

Both the origins of the Loopin and modified loopin equations are described in [20].

$$\begin{aligned} \varepsilon_{eq} &= \varepsilon_a \left(1 + \frac{\sigma_{mean}}{\sigma_a} \right)^\beta & \sigma_{mean} \geq 0 \\ \varepsilon_{eq} &= \varepsilon_a \left(1 - \frac{\sigma_{mean}}{\sigma_a} \right)^{-\beta} & \sigma_{mean} < 0 \end{aligned} \quad (17)$$

where σ_a is the amplitude of the local stress and β is a material parameter.

⁵ True fracture strength is defined as the load at failure divided by the actual cross-sectional area at failure

iii) Modified Loopin equation [20]

$$\begin{aligned}
\varepsilon_{eq} &= \varepsilon_a \left(1 + \frac{\sigma_{mean}}{\sigma_a} \right)^\beta & \sigma_{mean} \geq 0 \\
\varepsilon_{eq} &= \varepsilon_a \left(1 - \frac{\sigma_{mean}}{\sigma_a} \right)^{-\alpha/\beta} & \sigma_{mean} < 0
\end{aligned} \tag{18}$$

where α and β are material parameters.

iv) Walker equation [21]

$$\varepsilon_{eq} = \varepsilon_a^m \left(\frac{|\sigma_{max}|}{E} \right)^{1-m} \tag{19}$$

where σ_{max} is the peak stress and m is a material parameter.

v) Smith Watson Topper (SWT) equation [22]

$$\begin{aligned}
\varepsilon_{eq} &= \left(\varepsilon_a \frac{\sigma_{max}}{E} \right)^m & \sigma_{max} \geq 0 \\
\varepsilon_{eq} &= 0 & \sigma_{max} < 0
\end{aligned} \tag{20}$$

The Smith Watson and Topper mean stress equation is a general formulation that has been shown to correlate well with the fatigue experiments of aluminium alloys [23].

vi) Modified F-18 equation [22, 24]

The report by Ghidella et. al. [24] provides a good background to the development of the F-18 equivalent strain equation. An important point to note is that the equation was developed using data that did not include negative mean stresses.

$$\begin{aligned}
\varepsilon_{eq} &= \varepsilon_a + \left(\frac{\sigma_{mean}}{\gamma E} \right)^\beta & \sigma_{mean} \geq 0 \\
\varepsilon_{eq} &= \left(\varepsilon_a + \left(\frac{\sigma_{mean}}{\gamma E} \right)^\beta \right) \frac{2}{1-R} & \sigma_{mean} < 0
\end{aligned} \tag{21}$$

where γ is a material parameter.

4.6 Fatigue Damage Accumulation

The fatigue damage caused by one cycle is defined by the reciprocal of the number of repetitions of that cycle needed to cause failure. The loss of energy per hysteresis loop is

additive which leads to the assumption that fatigue damage is also additive (i.e. the Palmgren-Miner rule [25]). This linear damage accumulation concept was first proposed by Palmgren in 1923 [26] and Miner provided the mathematics to describe it in 1945 [25].

Consequently, the fatigue damage produced by n cycles at one strain level is defined as

$$D = \frac{n}{N} \quad (22)$$

where

- n is the number of applied cycles at strain range level $\Delta\epsilon_a$;
- N is the total number of cycles to cause failure at the strain range level $\Delta\epsilon_a$, read off the strain-life curve for the given stress range level.

If the spectrum consists of repeated cycles at one constant strain amplitude, then failure is assumed to occur when $n = N$ and thus the damage $D = 1$

For a variable amplitude load history containing more than one strain range, fatigue damage can be calculated as the sum of the damage attributable to each individual strain range level within the spectrum. That is

$$\sum D_i = \sum \frac{n_i}{N_i}. \quad (23)$$

Failure is assumed to occur when

$$\sum D_i \geq 1. \quad (24)$$

This linear summation of damage caused by different strain ranges is known as the Palmgren-Miner rule [25]. To apply this summation rule, the spectrum must first be analysed to identify the closed hysteresis loops using a scheme such as Rainflow counting. Each hysteresis loop is converted to an equivalent strain cycle with zero mean stress using an appropriate equivalent strain equation. Following this step, the Palmgren-Miner rule equation 23 can be applied to obtain the total damage resulting from the spectrum. Once the damage calculated using equation 23 exceeds 1, failure of the structure is assumed to occur. In the FAMSH implementation, the inverse of the total damage in equation 23 is used to calculate the number of times (passes) the spectrum is applied, such that the total damage is 1.0. This number is then used to determine the total fatigue life in flight hours using the flight hour's one spectrum represents.

Presently FAMSH only implements the Palmgren-Miner rule to calculate fatigue damage but it must be remembered that there are other techniques of fatigue damage calculation. Since 1945 a plethora of methods have been proposed to evaluate fatigue damage, mainly to account for the observed effect of the load sequence on the total life of structures [27].

5. Using FAMSH in CGAP

5.1 Starting FAMSH

When CGAP is launched from the Microsoft Windows Start menu, the user is presented with the screen as shown in Figure 9. By default the first module displayed is the CGAP Solver for crack growth analysis.

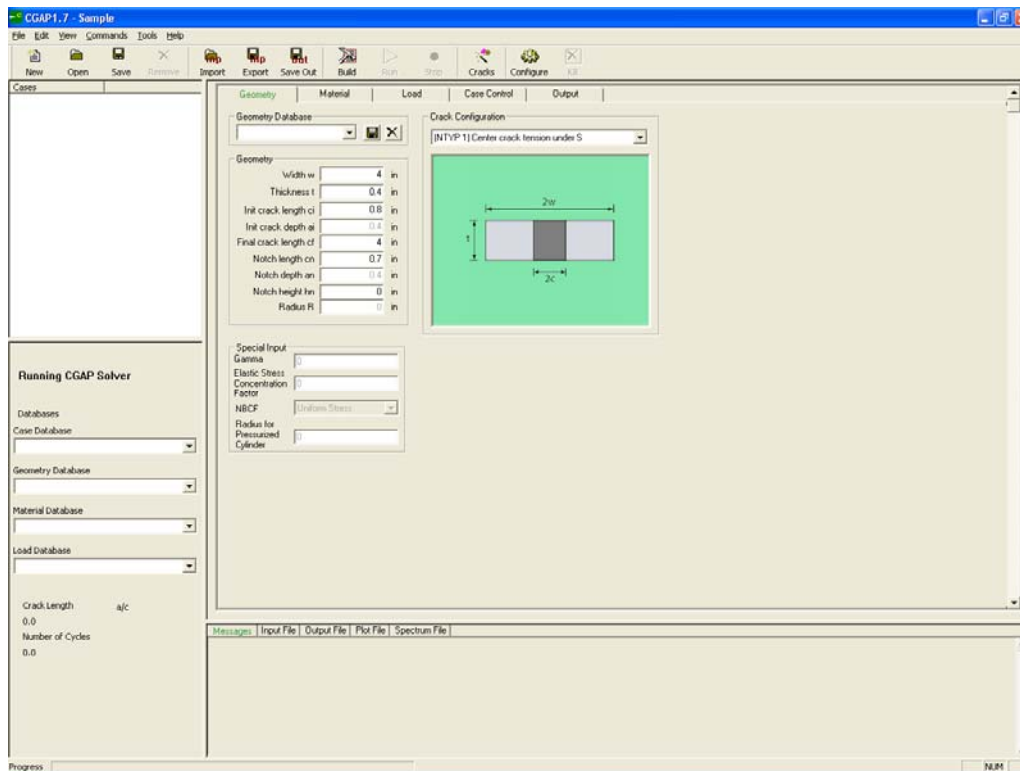


Figure 9: Default Start up mode for CGAP

To use the strain-life model the user must first switch to the FAMSH module in the CGAP GUI. This can be achieved in two ways:

Either by pressing the “**Configure**” button located in the top tool bar or by selecting “**tools → configuration...**” on the menu bar. The following “**Settings**” dialog box should appear Figure 10.

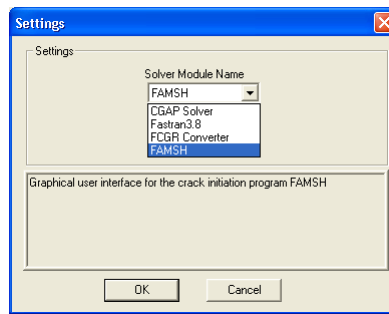


Figure 10: The CGAP settings dialog box

In this dialog box click the drop down box titled “**Solver Module Name**” and select “**FAMESH**”. Then click “**OK**”.

FAMESH should automatically link to the database file on installation, however the database can be selected or reselected at a later stage by using the “**Open Database File**” option under the “**File**” menu.

The FAMESH module should now be loaded and you are ready to begin. The module should look like Figure 11. The words “**Running FAMESH**” should appear in the bottom left panel to indicate that the FAMESH module has loaded properly.

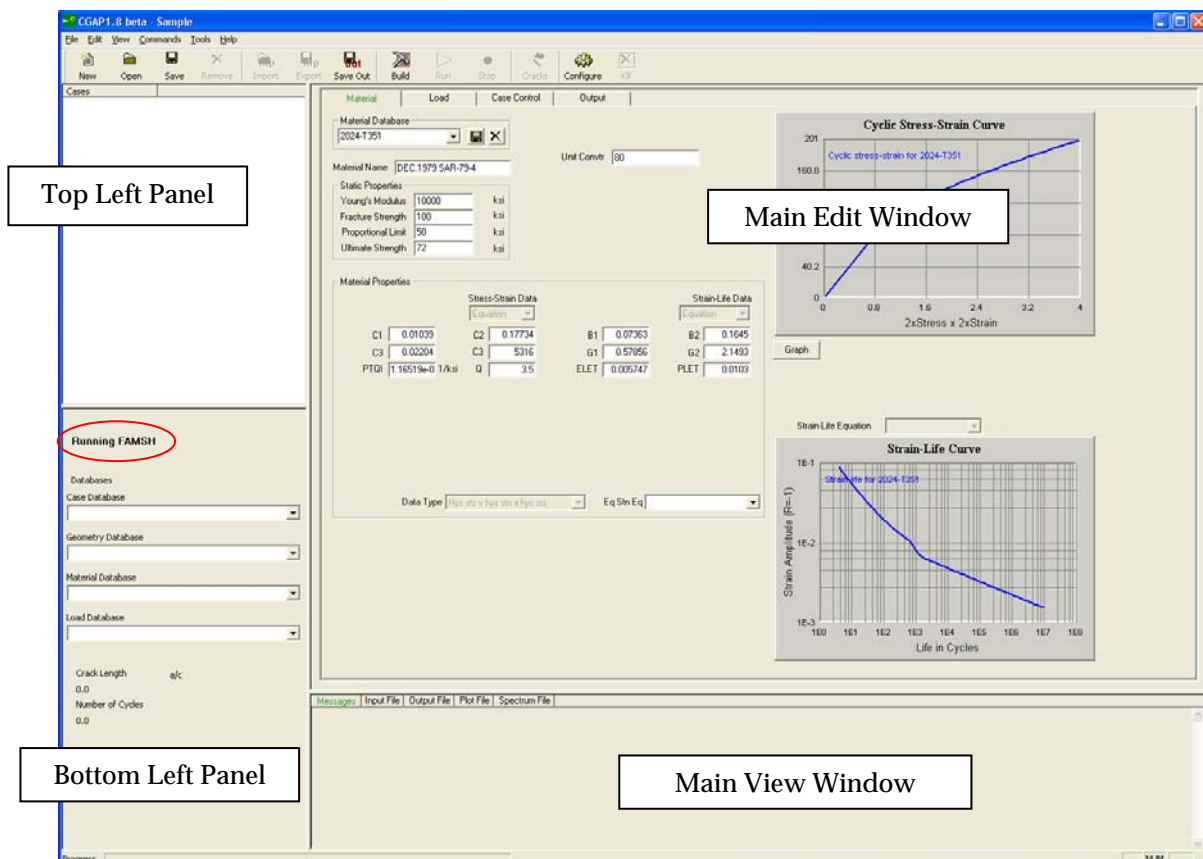


Figure 11: FAMESH module loaded in CGAP

5.2 Data Inputs and Outputs

The Filename.input file can be created manually and used as an input, but CGAP will create this file for the user when the user input their data into the GUI.

The input files used to specify a problem prior to analysis are as follows:

- Filename.input
- Filename.spectra
- Ftn07 (Required only for DSA⁶ formats)
- Ftn15 (Optionally, the single value contained in this file may be entered in Filename.input, on the last line with the keyword “Maximum Delta Stress:” followed by a value such as 60000)

The output files that are created by the CGAP FAMSH module are:

- Filename.input
- Filename.passes
- Filename.truncspc
- Filename.dsout
- Filename.dmo
- Flmat1.dat
- Flmat2.dat

See section 5.8 for more detail.

There are two ways to enter input data:

- Open an existing input file, e.g., from previous analysis;
- Enter data directly through CGAP GUI.

In either case the main input file has the extension “**.input**” and it contains all the control information for the analysis. The spectrum file has the extension “**.spectra**” and it contains the load spectrum, defined by turning points. The damage source code file is entitled “**ftn07**” and it contains the codes for different missions comprising the spectrum, see reference [2]. These codes are called “Damage Source Assignments” or DSAs⁷. Optionally, a file “**ftn15**” containing a single number representing the maximum stress range in the spectrum can be used. The “**.input**” file can be created with CGAP by entering data into CGAP directly and pressing the “**Build**” button. The spectrum file and the damage source code file are normally generated by upstream software but can also be created using a text editor. The material specifications are contained in either the “**flmat1.dat**” (tabulated data) or the “**flmat2.dat**” (equation specification) files. These files are generated automatically when the user selects a

⁶ Damage Source Assignments were developed for the P-3C SLAP. See reference [2] for more information.

⁷ The Damage Source Assignment was a modification made by Lockheed Martin to examine the proportions of damage associated with different in flight manoeuvres.

material from the material database in the CGAP GUI. These files can be used as inputs using the original FAMSH executable. The single number contained in “**ftn15**” is used to generate the damage distribution table, and does not affect the calculated fatigue life. The stress levels are categorised into 20 bins using this value. By default CGAP chooses 60000 if no number has been specified.

5.2.1 Units

To maintain consistency and backward compatibility with older versions of the FAMS and FAMSH codes it is recommended that the following units be used when entering data into CGAP.

Table 2: *Recommended input units for CGAP*

Input parameter	Units
Young's Modulus	ksi
Fracture Strength	ksi
Proportional Limit	ksi
Ultimate Strength	ksi
PTQI	1/ksi
All stresses in the stress-strain or stress-life table	ksi
Residual Stress (Resd)	ksi
MAXRNG	psi
Spectrum file	psi

5.2.2 Importing an Analysis File

Importing data can be accomplished using the “**Open**” button on the top tool bar or by clicking “**File→Open**”.

The input file is a text document with the extension “**.input**”. Table 3 gives an example of the input file and an associated list of the source code variables.

Table 3: An example of the input data file use in CGAP

Line No.	Example.input	FAMSH Variables	Line description
1	generic test seq	JTITL	Input title
2	1	IPT1	Material data output information
3	12	IPT2	Analysis Output Information
4	1	IPT3	Loads Data Format (ASCII or Binary)
5	0	IPT4	Damage Source Indicator
6	0	IPT5	Number of Passes
7	1	KN	Notch Factor
8	D7075-T651	MATERIAL	Material Identification
9	1	MATF	Material Data Type
10	1	UNITCV	Unit Conversion
11	0	RS	Residual Stress
12	2	NMLT	Number of Stress Multipliers
13	2.5 5	SREF	Stress Multipliers
14	1e-007	DCUT (9)	Damage Truncation Level
15	2		Equivalent strain equation
16	Flight Hours: 1		Spectrum file total flight hours*
17	Maximum Delta Stress:60000		Originally in a separate file "ftn15.dat"**

* Here, **Flight Hours:** and **Maximum Delta Stress:** are keywords and must be entered as shown.

** Lines 1-14 must be entered in the sequence shown. Lines 15-17 may be entered in any order, or any line may be omitted. When omitted, the equivalent strain equation defaults to 2, the flight hours default to 1 and the maximum delta stress defaults to 60000.

Input Title

On the first line any information can be input up to a length of 80 characters.

Material Data Output Information

This line contains an integer number that controls the type of material data written to the output data file. The following options are available:

- | | | |
|---|----------------------------|---|
| 0 | No material output - | No stress strain data is output |
| 1 | Cyclic Strain Stress - | A strain vs stress table is printed to the output file |
| 2 | Hysteresis Stress Strain - | A stress*strain vs stress table is printed to the output file |

Analysis Output Information

Another integer number is used to control the amount of information that is output to the output data file. The following options are available:

- | | | | |
|-----|----|----|---------------|
| -11 | or | -1 | Basic |
| 10 | or | 0 | Detailed |
| 11 | or | 1 | More Detailed |
| 12 | or | 2 | Most Detailed |

If the second number above is used then no *.passes file is produced. For more information see section 5.5.3.

Loads Data Format (ASCII or Binary)

This line contains an integer number that tells the program whether the spectrum file is in Binary or ASCII format

- | | |
|---|---------------|
| 0 | Binary format |
| 1 | ASCII format |

Damage Source Indicator

This is an integer number that tells the program whether the Damage Source Assignment (DSA) code is used. The DSA is a nine digit number that is used in the spectrum file and is used in the subsequent analysis and output [2]. For further information and an example of the application of damage source assignments refer to [28].

- | | |
|---|-----------------|
| 0 | DSA is used |
| 1 | DSA is not used |

Number of Passes

An integer number is used to switch between one pass and two passes. A residual stress is calculated after one pass and is used in the calculation of fatigue life during the second pass. One pass will ignore any residual stress calculated after the first pass.

- | | |
|---|---------------------|
| 0 | Two passes required |
| 1 | One pass required |

Notch Factor

The notch factor is the Neuber notch factor K_N and not the stress concentration factor K_t . It should be noted that scaling factors are applied to this number using a different input parameter to be discussed later.

Material Identification

This variable is a character string of length 25. In earlier versions the character string was limited to 9 characters. This variable specifies the material to be used and reflects the exact name used in the material database. If the name does not exist in the database a warning will be displayed by the CGAP GUI.

Material Data Type

MATF is an integer that indicates whether material data is specified in table format or as an equation. If “1” is selected then the program expects the material data to be in a table look-up format in a file with the name “flmat1.dat”. If “2” is selected then the program expects the material data to be in the form of an equation specified in the “flmat2.dat” file. This will be automatically selected by CGAP using the information in the database.

- | | |
|---|---------------|
| 1 | Table look-up |
| 2 | Equation |

Unit Conversion

This line contains a real number which is used to convert the units of the material data file. To convert from KSI to MPa use the conversion factor of 6.895. It does not affect the loads in the spectrum file.

Residual Stress

This line contains the magnitude of the residual stress needed in the analysis. If no residual stress is to be used, then enter 0.0. The units of the residual stress must be consistent with the units of the proportional limit, that is ksi.

Number of Multipliers

This integer parameter is used to specify the number of Stress multipliers to use. The multipliers are specified on the next line of the input data file.

Stress Multipliers

An array is used to store a maximum of 10 real numbers. Each number in the array specifies a multiplication factor to use in conjunction with the notch factor. The notch factor is multiplied by one of the stress multipliers which in turn is used to scale the applied spectrum. Analysis occurs for each of the stress multipliers. If the notch factor is given a value of 1 then stress multipliers can be used to specify a series of different notch stress concentration factors.

Truncation Level

This line contains a real number that is used to denote the user specified truncation level. This truncation level truncates the spectrum based on the associated damage calculated for each cycle. The number used here is a damage level below which cycles with damage less than this value are ignored.

Equivalent Strain Equation

An integer number is used to select the equivalent strain equation to use in the analysis. Several equivalent strain equations are available for the user and are as follows. Section 4.5 describes these equations in greater detail.

2 *Modified Morrow equation*

The next options required extra information to be placed in the “.input” file. The extra information is entered on the next line following the equivalent strain equation option in the “.input” file.

3 *Loopin*

The beta parameter in the Loopin equation is required on the next line underneath 3

4 *Modified Loopin*

Two parameters used in the Modified Loopin equation, beta and alpha, are required on the next line underneath 4

5 *Walker*

A parameter “m’ used in the Walker equation is required on the next line underneath 5

6 *Smith-Watson-Topper*

A parameter “m’ used in the Smith-Watson-Topper equation is required on the next line underneath 6

7 *Modified F-18*

Two parameters used in the Modified F-18 equation, beta and gamma, are required on the next line underneath 7

Spectrum File Total Flight Hours

This number specifies the number of flight hours the spectrum represents. The text “**Flight Hours:**” must be entered exactly as shown followed by the number of flight hours.

Maximum Delta Stress

The largest change in stress in the spectrum is used in the calculation of damage densities. The text “**Maximum Delta Stress:**” must be entered exactly as shown followed by a number. The value here is not critical to the final life estimates produced. The function of this variable influences the bin sizes used in determining the percentage of damage caused by different loads. This information is recorded in the filename.dsout output.

There are three tabs that are used to enter data. They are the “**Material**”, “**Load**” and “**Case Control**” tabs.

5.3 Material tab

The material tab (see Figure 12) allows the user to create a new material, or load or update an existing material in the database. The material properties, including Young’s modulus, the proportional limit, the fracture strength, the ultimate strength, the stress-strain relationship and the strain-life relationship are available to all the cases using the same database. This tab also allows the user to select the strain-life equation, equivalent strain equation and to enter related parameters. These data are not stored in the database; they are saved in the `input` file, and hence only available for the current case being analysed.

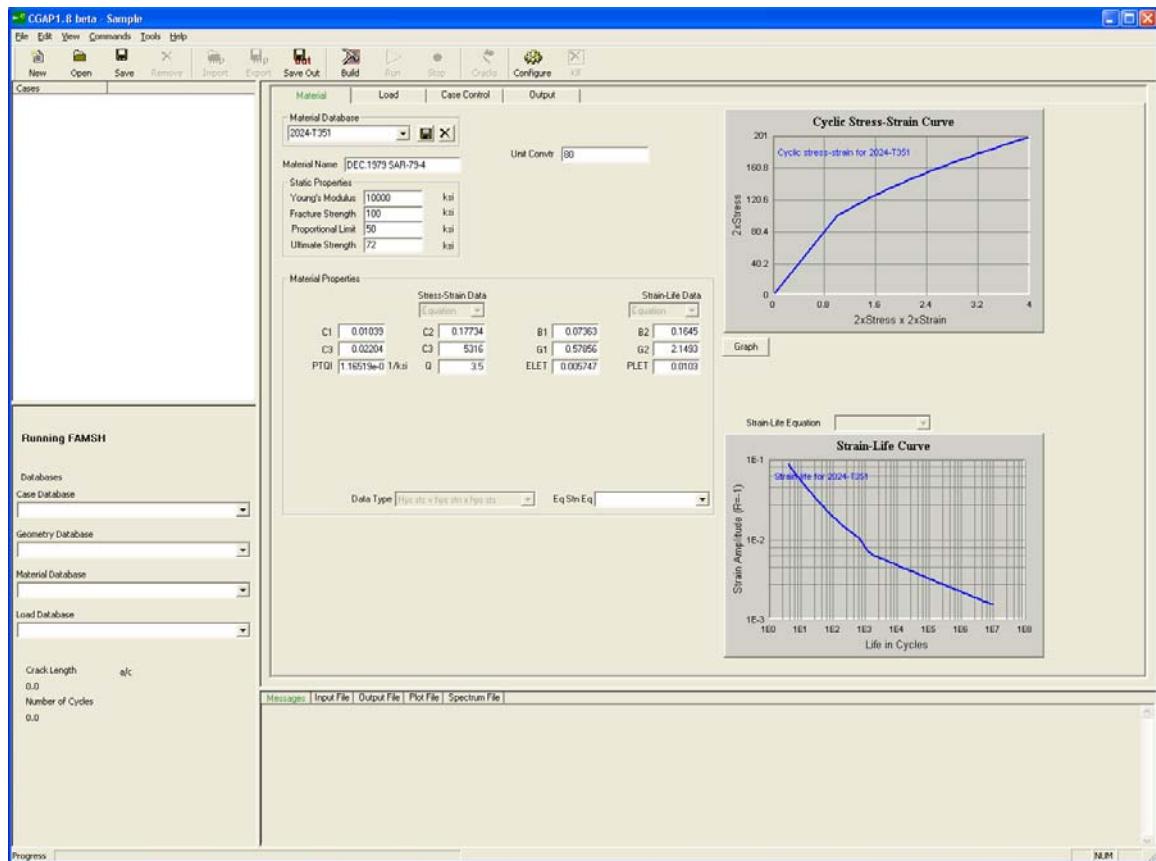


Figure 12: The materials tab used in the FAMSH CGAP module

5.3.1 Loading an Existing Material

Materials from the database can be selected using the Material Database dropdown menu, see Figure 13.

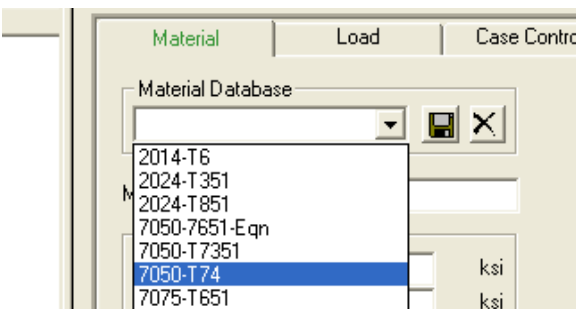


Figure 13: The material drop down menu

5.3.2 Creating a New Material Database Entry

To create a new material, enter a new name or modify an existing material ID in the Material Database dropdown box. This will enable two dropdown menus: **Stress-Strain**

Data” and **“Data Type”**. The user may now select either the tabular input or the equation input option from the **“Stress-Strain Data”** dropdown menu, see Figure 14.

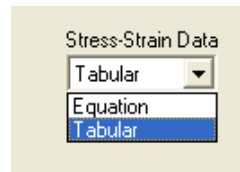


Figure 14: Stress-Strain Data dropdown menu

The **“Data Type”** dropdown menu (see Figure 15) can be used to specify the form of the stress-strain relationship. This option only affects data entered in tabular form; it does not affect the equation format. The equation parameters always define the cyclic stress-strain relationship. Three **“Data Type”** options are available

- Hys sts v hys stn \times hys sts (Hysteresis stress versus hysteresis strain \times hysteresis stress)
- Cyc stress v cyc strain (Cyclic stress versus cyclic strain)
- Hys stress v hys strain (hysteresis stress versus hysteresis strain)

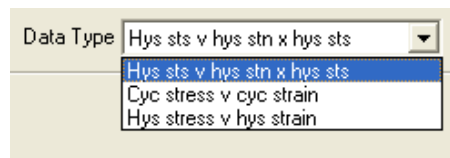


Figure 15: Data Type dropdown menu

Data can be entered directly into the grids provided, as shown in Figure 16. The number of data is specified for both the stress-strain curves and the strain-life curves.

	Cyclic Strain	Cyclic Stress
1	0.00587	60.5
2	0.00612	63
3	0.00636	65.5
4	0.0066	68
5	0.00685	70.5
6	0.00708	73

	Life	Strain Amp
1	92	0.0195759
2	194	0.0144739
3	296	0.0125531
4	398	0.0114951
5	500	0.0108079
6	602	0.0103177

Figure 16: Material tabular input in the FAMSH CGAP module

Data entered in the table can be deleted by right clicking the specific data you wish to delete and selecting “**Delete**”, see Figure 17.

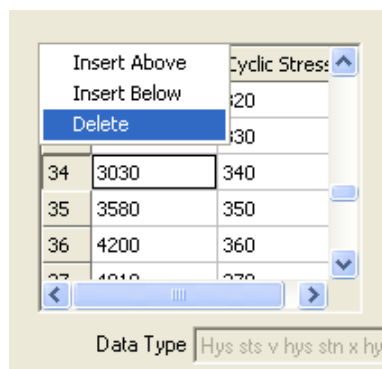


Figure 17: Deleting data in the material data tables

Material data can also be input in the form of equations. Selecting “**Equation**” from the Stress-Strain Data dropdown menu will allow the user to enter the relevant constants that specify the material equations used in FAMSH. An example of the material property specification is shown in Figure 18.

Figure 18: Material equation input in the FAMSH CGAP module

The stress-strain equation used in FAMSH (equation 8) is presented in section 4.1.2. In FAMSH the input parameters used are PTQI and Q and relate to the cyclic strength coefficient K' and cyclic strain hardening coefficients n' via the following equations:

$$PTQI = \frac{1}{K'} \quad (25)$$

$$Q = \frac{1}{n'} \quad (26)$$

Refer to section 4.3 for a detailed description of the constants used in FAMSH to define the strain-life equation. Appendix B explains how to determine these parameters from experimental data.

Once the data has been entered, the new material specification must be saved to the database. To do this press the save button (see Figure 19) next to the Material Name input box.

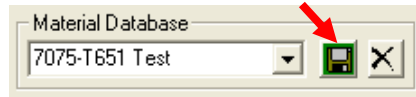


Figure 19: Click the save button to save the material to the database

To remove the material from the database use the button marked with a cross next to the save button in Figure 19.

5.3.3 Eq Stn Eq (Equivalent Strain Equation)

The equivalent strain equation is also selected under the materials tab. The available options are detailed in section 4.5.

5.3.4 Strain-Life Equation

This menu is for information only and is not selectable by the user. Its function is to indicate which strain-life equation is being used in conjunction with the equivalent strain equation. When this box either contains the word “equation” or remains empty then the default stain life equation, equation 12 is used. If it shows “Tabular”, then the tabular strain-life data is used.

5.3.5 UnitCv (Unit Conversion)

The variable UnitCv is used to convert the units of the material properties. For example, to convert from the Imperial unit ksi to the SI unit MPa, a value of 6.895 should be used. It does not affect the loads in the spectrum file.

5.4 Load tab

The load tab (see Figure 20) allows the user to select the spectrum file and to enter a number of load-related parameters.

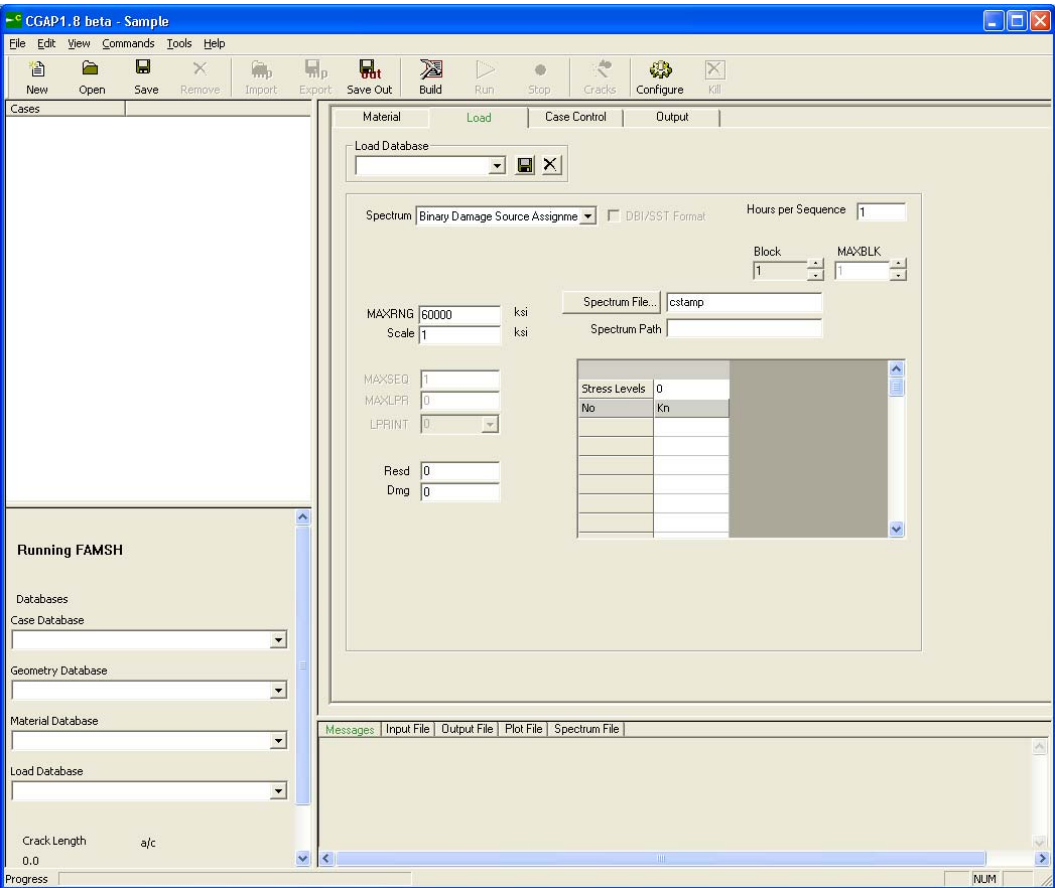


Figure 20: The load tab used in the FAMSH CGAP module

5.4.1 Spectrum File...

The spectrum file is loaded using the “**Spectrum File...**” button. By default the spectrum file has the extension “.spectra”.

5.4.2 Spectrum

The user must indicate if the spectrum file contains DSA information; whether it is in binary or text format. This is done by selecting the appropriate option under the load tab using the Spectrum dropdown menu. There are four options available and shown in Figure 21.

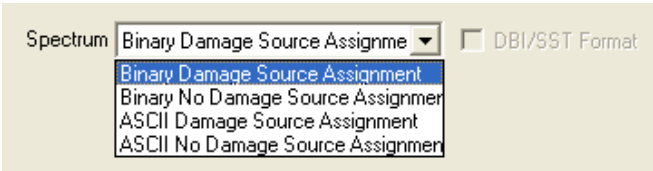


Figure 21: Spectrum dropdown menu

A fifth option is available “DBI/SST” format⁸. This can be selected by choosing “*ASCII Damage Source Assignment*” and checking the “**DBI/SST Format**” box next to the “**Spectrum**” dropdown menu. For further information on DBI/SST format refer to [6].

5.4.3 MAXRNG (Maximum Delta Stress)

The number entered here is the maximum applied stress range, which is used to calculate damage distribution. The maximum stress range can be calculated by subtracting the minimum spectrum stress from the maximum spectrum stress, but currently a value of 60000 is used by default. It should be noted that this value does not affect the calculated fatigue life. This value will be calculated automatically in the next version of FAMSH.

5.4.4 Scale

This was originally referred to as K_n in the FAMS code, but has been renamed to Scale in CGAP to better reflect its functionality. This value is essentially a scaling factor to the spectrum. The actual applied stress is the product of this value, the level of loading and K_n .

5.4.5 Resd (Residual Stress)

Residual stress can be introduced using the “**Resd**” input under the load tab. The residual stress should use the same units as the proportional limit.

5.4.6 Dmg (Damage cut off)

This is the damage cut off threshold DCUT. This specifies the truncation level. That is it truncates loads in the spectrum with damage less than DCUT.

5.4.7 Hours per sequence

This value is used to convert the life in cycles to flight hours. This number appears in the “**.input**” file after the key phrase “**Flight Hours:**”

⁸ The DBI/SSI format was developed to support the P-3C service life assessment program and was used to examine the damage resulting from different flight conditions.

5.5 Case Control tab

The Case Control tab (see Figure 22) allows the user to select appropriate output options.

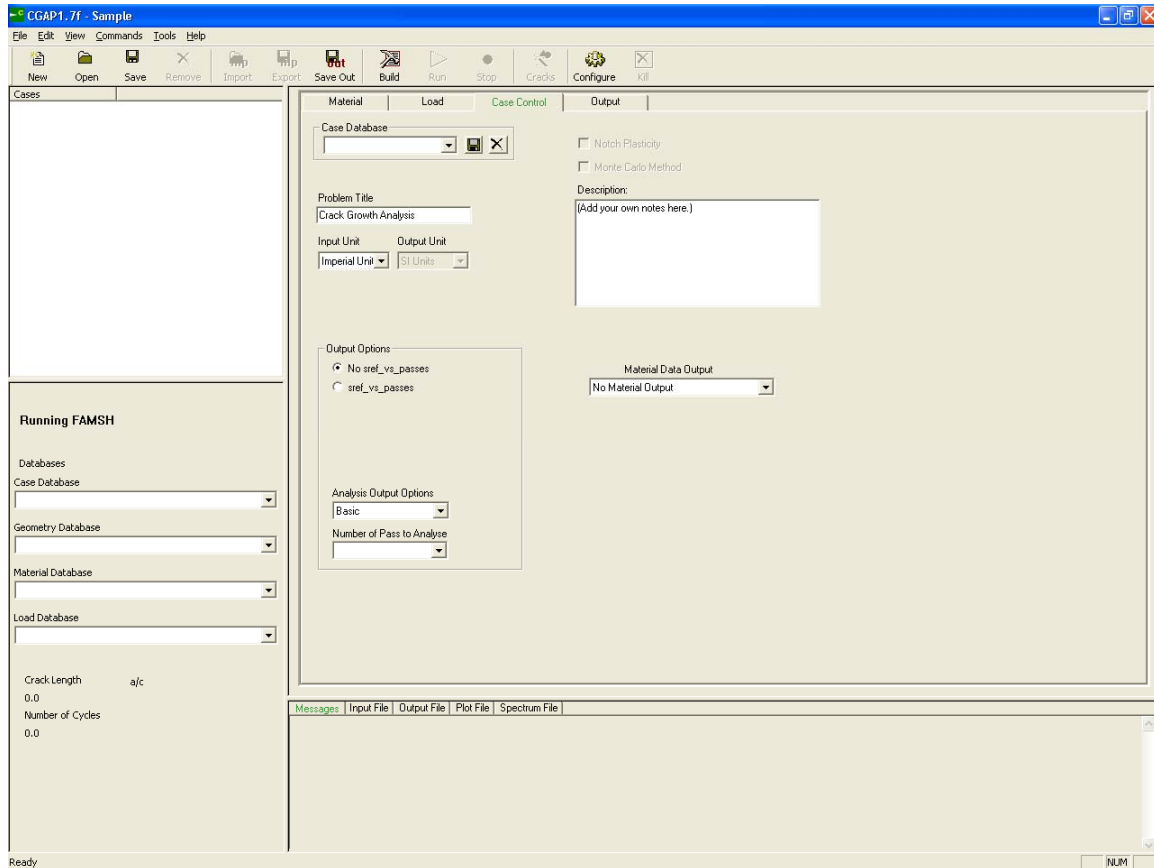


Figure 22: The Case Control tab used in the FAMSH CGAP module

5.5.1 Problem Title

Under this tab the user can add a title to the output using the “**Problem Title**” input box.

5.5.2 No sref_vs_passes/sref_vs_passes

The user can also choose to create a “.passes” file by toggling between “**No sref_vs_passes**” and “**sref_vs_passes**”. See section 5.8 for more information.

5.5.3 Analysis Output Options

There are four options under the “**Analysis Output Options**” dropdown menu. The user has the option to choose from “**Basic**”, “**Detailed**”, “**More Detailed**” and “**Most Detailed**”. These options control the amount of information written to the “.output” file during analysis. Basic level information reports the total damage calculated and the total life as well as other low level model information. Detailed information additionally reports on the damage each block in the spectrum produces. More Detailed output also includes the Rainflow cycles in the

spectrum and the notch stress and strain calculated for each of these cycles. The most detailed option also gives information about the notch stress and strain, the alternating strain, mean stress, equivalent stress, failure cycles and the damage for each cycle.

5.5.4 Material Data Output

Under the “**Material Data Output**” dropdown menu the user can choose what material data to output to the output file. The user has the choice of “**No material output**”, “**Cyclic Stress-Strain**” and “**Hysteresis Stress-Strain**”. The “**Cyclic Stress-Strain**” option outputs a table of data describing the cyclic stress-strain curve. The “**Hysteresis Stress-Strain**” option outputs a table of data that describes the hysteresis stress-strain curve.

5.5.5 Passes

The “**Passes**” dropdown menu provides the user the option to use one or two passes in the analysis process.

5.6 Spectrum file formats

There are essentially five spectrum file formats available and they are:

- Block format with Designated
- Damage Source Assignment (DSA)
- Block format without Damage Source Assignment (DSA)
- Cycle format with Damage Source Assignment (DSA)
- Cycle format without Damage Source Assignment (DSA)
- DBI/SST input format

The format of the spectrum files is important if the analysis is to run correctly. The following sections describe in detail the format to use for each of the spectrum file formats.

5.6.1 Block format with Damage Source Assignment (DSA)

The layout and format of the spectrum file that is required when using the Damage Source Assignment and Block type inputs is presented in Table 4.

Table 4: The format of a FAMSH input file using DSA and Block formats (fixed format)

Example_DSA_Block.input

2		1		BLOCK			
The number of flights		Arbitrary number that is not used		Spectrum format			
1		38		FLIGHT NUMBER & MISSION TYPE			
Flight number		Mission Type		General description not used in the analysis			
2		1.000		TURNING POINT PAIRS & FLIGHT DURATION			
Number of lines in the flight		Flight Duration		General description not used in the analysis			
38001022		1		-13408		4	
DSA		Maximum TP stress		Minimum TP stress		Number of TPPs	
38003019		6891		1087		2	
12 spaces Integer		10 spaces Real		10 spaces Real		10 spaces Integer	

Each number should be contained within the allocated spaces

5.6.2 Block format without Damage Source Assignment (DSA)

The layout and format of the spectrum file that is required when using Block type inputs and no DSA is presented in Table 5. Note that the arbitrary number seen in the DSA block format in the first line should be removed. Also note that the maximum and minimum stresses should be expressed using integer numbers and not real numbers.

Table 5: The format of a FAMSH input file using the Block format with no DSA

Example_no_DSA_Block.input		
<div> <div>1</div> <div>BLOCK</div> <div>The number of flights</div> <div>Spectrum format</div> </div>		
<div> <div>Example Flight Spectra</div> <div>Title of the spectrum</div> </div>		
<div> <div>2</div> <div>1.000</div> <div>TURNING POINT PAIRS & FLIGHT DURATION</div> <div>Number of TPPs in the flight</div> <div>Flight Duration</div> <div>General description not used in the analysis</div> </div>		
<div> <div>1</div> <div>-13408</div> <div>4</div> <div>Maximum TP stress</div> <div>Minimum TP stress</div> <div>Number of TPPs</div> </div>		
<div> <div>6891</div> <div>1087</div> <div>2</div> <div>10 spaces Integer</div> <div>10 spaces Integer</div> <div>10 spaces Integer</div> <div>Each number should be contained within the 10 spaces</div> </div>		

5.6.3 Cycle format with Damage Source Assignment (DSA)

The layout and format of the spectrum file that is required when using the Damage Source Assignment and Cycle type inputs is presented in Table 6.

Table 6: The format of a FAMSH input file using DSA and Cycle formats

Example_DSA_Cycle.input			
2		1	CYCLE
The number of flights		Arbitrary number that is not used	Spectrum format
1	38	FLIGHT NUMBER & MISSION TYPE	
Flight number	Mission Type	General description not used in the analysis	
114	1.000	TURNING POINT PAIRS & FLIGHT DURATION	
Number of TPPs in the flight	Flight Duration	General description not used in the analysis	
38001022	1.00	38001022	-13408.00
DSA	Maximum TP stress	DSA	Minimum TP stress
The user has the option to enter another TPP on the same line			
38002023	-1773.00	38002023	-9068.00
12 spaces Integer	10 spaces Real	10 spaces Integer	10 spaces Real
Each number should be contained within the allocated spaces			
One Space	One Space	One Space	

5.6.4 Cycle format without Damage Source Assignment (DSA)

The layout and format of the spectrum file that is required when using Cycle type inputs and no DSA is presented in Table 7. Note that the arbitrary number seen in the DSA block format in the first line should be removed.

Table 7: The format of a FAMSH input file using the Cycle format with no DSA

Example_no_DSA_Cycle.input				
1		CYCLE		
The number of flights		Spectrum format		
Example Flight Spectra				
Title of the spectrum				
114	1.000	TURNING POINT PAIRS & FLIGHT DURATION		
Number of TPPs in the flight	Flight Duration	General description not used in the analysis		
1.00	-13408.00	-1773.00	-9068.00	The user has the option to enter up to 4 TPPs on the same line
Maximum TP stress	Minimum TP stress	Maximum TP stress	Minimum TP stress	
6891.00	1087.00	15104.00	5740.00	Each number should be contained within the 10 spaces
10 spaces Real	10 spaces Real	10 spaces Real	10 spaces Real	

5.6.5 DBI/SST input format

The layout and format of the spectrum file that is required when using the DBI/SST type inputs is presented in Table 8.

Table 8: The format of a FAMSH input file using DBI/SST formats

Example_DBI_Cycle.input							
2		1		CYCLE			
The number of flights		Arbitrary number that is not used		Spectrum format			
1		38		FLIGHT NUMBER & MISSION TYPE			
Flight number		Mission Type		General description not used in the analysis			
114		1.000		TURNING POINT PAIRS & FLIGHT DURATION			
Number of TPPs in the flight		Flight Duration		General description not used in the analysis			
0005001091	869.62	0005001091	295.63	0005004072	3884.06	0005004072	-1068.51
DSA	Maximum TP stress	DSA	Minimum TP stress	DSA	Maximum TP stress	DSA	Minimum TP stress
0005004072	3884.06	0005004072	-1068.51	0005004072	4819.06	0005004072	-1690.94
10 spaces Integer	10 spaces Real	10 spaces Integer	10 spaces Real	10 spaces Integer	10 spaces Real	10 spaces Integer	10 spaces Real
One Space	One Space	One Space	One Space	One Space	One Space	One Space	One Space

5.7 Analysis Using FAMSH

Performing the analysis using CGAP is rather simple. Once the relevant data has been input into CGAP, all the user needs to do is to press the “**Build**” button to build the case and then press “**Run**” to execute the analysis, see Figure 23.

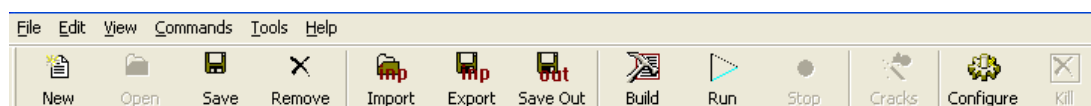


Figure 23: CGAP menu bar

Active analysis is indicated by the progress bar at the bottom of the window, see Figure 24.



Figure 24: Progress bar

When the analysis is complete, a message will be displayed in the messages pane at the bottom of the window.

5.8 FAMSH output

Several outputs are created by FAMSH. A brief description of each of the output files is given in Table 9. Examples of the output are provided in Appendix C.

Table 9: FAMSH output files

Output File	Description	Example
filename.dmo	The .dmo file contains the damage matrix. The damage matrix provides the user with information relating to the distribution of damage based on the mission types. This information is only available when the DSA format is used.	Table 23
filename.dsout	This file records the damage density table calculated using the maximum change in stress defined in the ftn15 file or input file. The .dsout file is equivalent to the ftn13 file produced by FAMS.	Table 24
filename.passes	The first line of this file contains the path of the input file. The following lines contain the Kn values specified in the input file using the source variable SREF along with the evaluated fatigue life in flight hours to failure.	Table 25
filename.truncspc	This file contains the damage based truncated spectrum. This file is equivalent to the ftn11 file produced by FAMS.	Table 26
filename.output	This file contains all the output produced by FAMSH. The information in the output file is controlled by the case control tab in CGAP.	Table 27

6. Material Database

CGAP incorporates a new material database that links seamlessly with the CGAP environment for crack growth and fatigue analysis. The database allows the user to select, retrieve and store material properties to perform analyses. The use of an integrated material database, in comparison to individual material data files, provides greater consistency. This thereby minimises errors associated with incorrect material input files and improves traceability of the analysis results. The database also provides support to quality control of outputs of the analyses for certification and validation purposes.

6.1 Materials Data Structure

A diagram of the CGAP materials data structure is provided in Figure 25. The fields in the four data tables pertaining to crack initiation properties are described in Table 10.

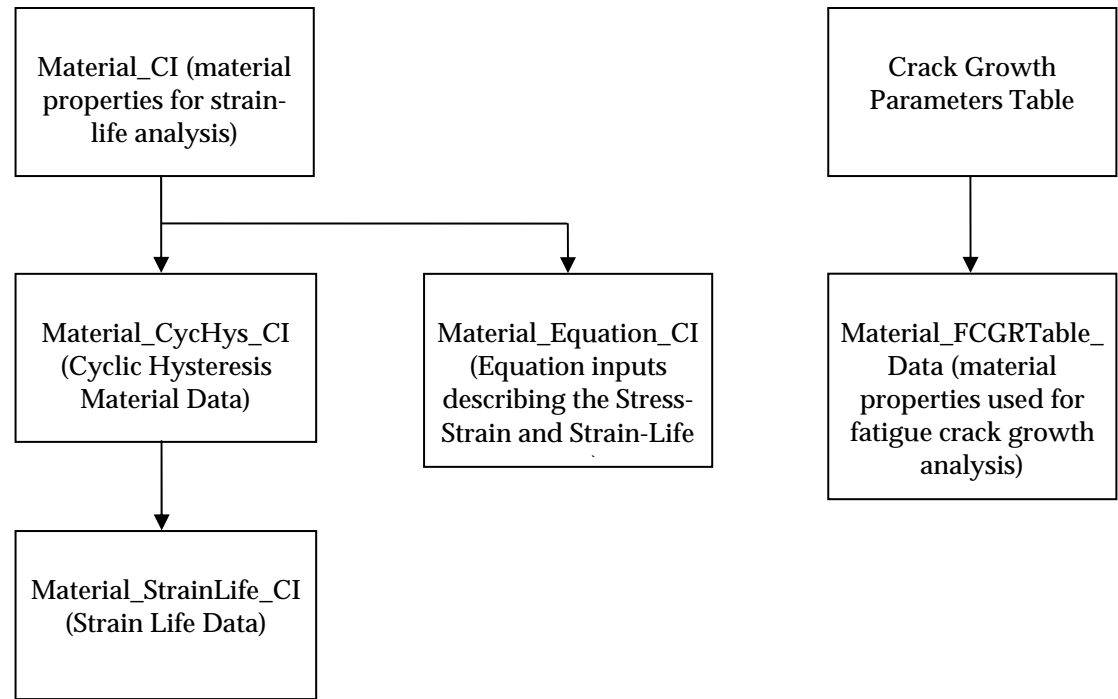


Figure 25: CGAP Material Data Structure Diagram

Table 10: CGAP Materials Data Structure Description

Table Name	Table Description	CGAP Database Field	FAMSH Variable	Description
Material_CI	Contains unique material identifier as well as common material properties. Links with all the other crack initiation parameter tables.	id	MTITLE(1:9)	Material specification
		name	MTITLE(10:45)	Material description
		MatFormat	MATF	The material format MatFormat = 1 Tabular MatFormat = 2 Equation
		E	E	Young's Modulus
		Sproportional	PLMT	proportional limit
		Sultimate	FULT	ultimate strength
		NPTH	Sfracture	fracture strength
		N_pts_CycHys	SF	the number of cyclic/hysteresis data pairs
		N_pts_EN	NPTS	the number of material strain-life data pairs
		CycHysType	IM	a flag that specifies the type of cyclic/hysteresis data IM = 1 – cyclic strain versus stress data IM = 2 – hysteresis strain versus stress data IM = 3 – hysteresis stress-strain versus stress data
Material_CycHys_CI	Contains crack initiation data for cyclic /hysteresis stress-strain curves represented by discrete data points (from <i>flmat1.dat</i> file). Links with Material_CI and Material_StrainLife_CI tables.	factor	FCTR	the factor required to convert data from ksi into psi
		id	MTITLE(1:9)	Material specification
		CycHysData	HYS1(NPTH)	contains either cyclic strain, hysteresis strain or hysteresis stress-strain data.
		StressData	HYS2(NPTH)	contains stress data.

Table Name	Table Description	CGAP Database Field	FAMSH Variable	Description
Material_StrainLife_CI	Contains crack initiation data for material strain-life curves represented by discrete data points (from <i>flmat1.dat</i> file). Links with the Material_CycHys_CI table and Material_CI tables.	id	MTITLE(1:9)	Material specification
		StrainData	SNL1(NPTS)	contains material strain amplitude data.
		LifeData	SNL2(NPTS)	contains material life data in number of cycles.
Material_Equation_CI	Contains crack initiation data for the stress-strain relationship and the strain-life curves represented by equations (from <i>flmat2.dat</i> file). Links with the Material_CI table.	id	MTITLE(1:9)	Material specification
		PTQI, Q	PTQI, Q	Parameters used to describe the cyclic stress-strain curve (see section 4.1.2 for more information)
		C1, C2, C3, C4	C1, C2, C3, C4	Parameters related to the fatigue strength and ductility coefficients and exponents. See equation 12 and equation 13. Also see Appendix B for a suggested method to evaluate these coefficients.
		B1, B2, G1, G2	B1, B2, G1, G2	Exponents related to the fatigue strength and ductility exponents via equation 13. Also see Appendix B for a suggested method to evaluate these exponents.
		PLET, ELET	PLET, ELET	are strains chosen to define the transitions between region 1, 2 and 3

6.2 FAMSH interaction with the Material Database

The material properties stored in the database are used by FAMSH indirectly through one of two material files, *flmat1.dat* and *flmat2.dat*, automatically generated by the CGAP GUI. A sample of each of these files is provided in Appendix D. Both files contain basic material property data such as the Young's Modulus, yield and ultimate strengths. They also contain material cyclic/hysteresis curves and strain-life curves. They differ in that *flmat1.dat* represents the material curves via discrete data points, while *flmat2.dat* uses up to three equations to represent the cyclic/hysteresis and strain-life curves. A "flag" variable (MATF) within the FAMSH input file tells the program which material data file to utilise. The parameters and format of *flmat1.dat* and *flmat2.dat* are presented in Table 11 and Table 13 respectively. The definitions of the variables contained in *flmat1.dat* and *flmat2.dat* are presented in Table 12 and Table 14, respectively.

Table 11: Format of the *flmat1.dat* file

Line	File Parameters
1	P MTITLE
2	E PLMT FULT SF
3	NPTH FCTR IM
4	HYS1(1), HYS2(1) HYS1(2), HYS2(2) . . . HYS1(NPTH), HYS2(NPTH)
5	NPTS
6	SNL1(1), SNL2(1) SNL1(2), SNL2(2) . . . SNL1(NPTS), SNL2(NPTS)

Table 12: File parameter descriptions(*flmat1.dat*)

File Parameter	Description of the file parameter
P	a single character used by FAMSH to distinguish between a comment (represented by a ";") or a material header line (represented by a ">")
MTITLE	material title
E	Young's Modulus
PLMT	proportional limit
FULT	ultimate strength
SF	fracture strength
NPTH	the number of cyclic/hysteresis data pairs
FCTR	the factor required to convert data from ksi into psi
IM	a flag that specifies the type of cyclic/hysteresis data IM = 1 – cyclic strain versus stress data IM = 2 – hysteresis strain versus stress data IM = 3 – hysteresis stress-strain versus stress data
HYS1(NPTH)	array with either cyclic strain, hysteresis strain or hysteresis stress-strain data. Forms data pairs with HYS2(NPTH).
HYS2(NPTH)	array with stress data. Forms data pairs with HYS1(NPTH).
NPTS	the number of material strain-life data pairs
SNL1(NPTS)	array with material strain amplitude data. Forms data pairs with SNL2(NPTS).
SNL2(NPTS)	array with material life data in number of cycles. Forms data pairs with SNL1(NPTS).

Table 13: Format of the *flmat2.dat* file

Line	File Parameters					
1	P	MTITLE				
2	E	PLMT	FULT	SF	PTQI	Q
3	C1	C2	C3	C4		
4	B1	B2	G1	G2	PLET	ELET

Table 14: File parameter descriptions(*flmat2.dat*)

File Parameter	Description of the file parameter
P	a single character used by FAMSH to distinguish between a comment (represented by a “;”) or a material header line (represented by a “>”)
MTITLE	material title
E	Young’s Modulus
PLMT	proportional limit
FULT	ultimate strength
SF	fracture strength
PTQI, Q	Parameters used to describe the cyclic stress-strain curve (see section 4.1.2 for more information)
C1, C2, C3, C4	Parameters related to the fatigue strength and ductility coefficients and exponents. See equation 12 and equation 13
B1, B2, G1, G2	Exponents related to the fatigue strength and ductility exponents via equation 13
PLET, ELET	are strains chosen to define the transitions between region 1, 2 and 3

Note that FAMSH has limits on the size of the arrays associated with the *flmat1.dat* file. Arrays HYS1 and HYS2 can contain no more than 75 elements while arrays SNL1 and SNL2 can contain no more than 65 elements. CGAP has a limit of 50 elements.

7. Example

This section uses an example to illustrate the use of the FAMSH code. It is helpful to remember that the FAMSH module operates in a very similar manner to the FAMS code. Thus, we can expect similar outputs to be produced. For a detailed description with regard to the strain-life theory on which FAMSH is based, refer to section 4. The example presented in this section will be covered in four sections which will explain the Problem, Inputs, Execution and Results.

7.1 Problem

Consider a problem in which the same spectrum is applied at two locations on a structure manufactured from 7050-T7351 aluminium. The locations on the structure will be denoted location 1 and location 2. Both location 1 and location 2 have geometric features that result in a stress concentration. Assume that we know the Neuber stress concentration factors (K_N) in these locations are 2.5 and 5 respectively.

For the purposes of this example consider a spectrum composed of the following sub-blocks of constant amplitude loading, shown in Table 15.

Table 15: Example spectrum loading

Constant amplitude sub- block number	DSA	R ratio	S_{\max} (psi)	Number of Cycles
1	22	-1	12000	5
2	19	0.5	12000	20
3	5	0.8	10000	100
4	19	0.5	12000	20

The aim of the analysis is to determine the estimated time to failure at location 1 and location 2.

7.2 Inputs

We will call this example “Gen_seq” and name all our input files accordingly. To perform the analysis we need to create 3 input files. These files are the “.input”, “.spectra” and “ftn07” files.

The first step is to create the spectrum file. For this example the spectrum file will be in ASCII format, in blocks and using Damage Source Assignments, which can be created using any text editor. Section 5.6.1 presents the description of this format for the spectrum file.

Table 16 shows the complete spectrum file. Line 1 contains three numbers. The first number, “1”, indicates one flight has been defined in the spectrum file. The second number is a dummy variable which is not used in the analysis. Enter “1” as the second number. Finally the key word “BLOCK” should be entered to indicate that the spectrum file is defined in block format. Line 2 contains two numbers, the flight number and the mission type. The flight number is not used in the analysis but is used to indicate which flight the analysis refers to. Enter “101” for the flight number. The mission type identifies the mission using a number. In this example we are identifying the mission as mission 27 so enter “27” as the second number on line 2. Any text that is added following these numbers will not be used by FAMSH in the analysis.

Line 3 also contains two numbers; the first number is the total number of lines below Line 3 that define the spectrum, and the second number defines the flight duration. Since four lines are needed in this example to describe the flight, we enter “4” for the first number. For this problem let us further assume that the spectrum represents 100 flight hours so enter “100” for the second number. Although 100 is entered here it is not used in the analysis. The actual flight hours represented by the spectrum is input separately in the **.input** file.

The next four lines contain the information shown in Table 15. For this problem name the file “**Gen_seq.spectra**” and save it.

Table 16: The spectrum file

Gen_spec.spectra				
1	1	BLOCK		
101	27	FLIGHT NUMBER & MISSION TYPE		
4	100.0	CYCLE COUNT & FLIGHT DURATION		
27001022	12000	-12000.0	5	
27002019	12000	6000.0	20	
27003005	10000	8000.0	1000	
27004019	12000	6000.0	20.	
.				
.				

As this problem uses DSA's it requires an extra file to describe the DSA codes. This file is called "ftn07" and is also a text file. For this problem, create a file with the following information in Table 17 and save it with the name "ftn07".

Table 17: The ftn07 file

Ftn07				
'MISSIONS' 27				
'DAMAGE SOURCES' 3				
005	'R=0.8			
019	'R=0.5			
022	'R=-1			
.				
.				

To create the ".input" file you can either create it using a text editor or using CGAP. To use CGAP open CGAP and enter the FAMSH module as described in section 5.1. By default the materials tab should be displayed. Under the materials database dropdown box select 7050-T7351 as shown in Figure 26.

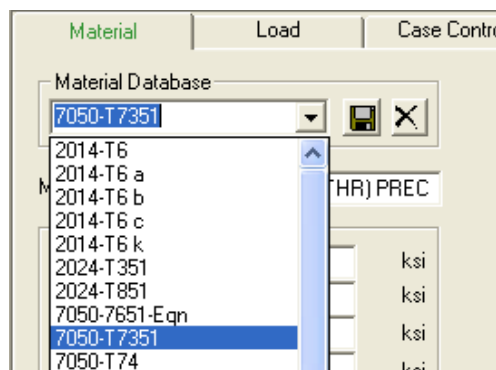


Figure 26: Materials tab Materials Database drop down menu

The materials tab will look like Figure 27 with the tabular material description active. Both the Cyclic Stress-Strain Curve and Strain-Life Curve figures should now be populated.

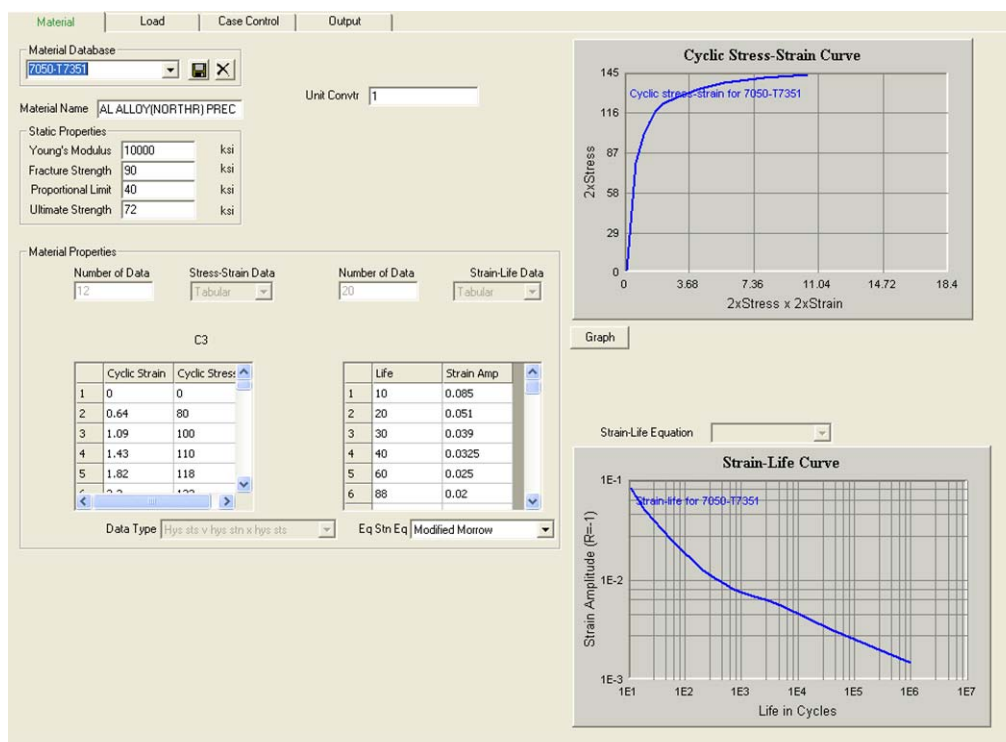


Figure 27: Materials tab with the tabular material description active

Now click on the “**Eq Stn Eq**” dropdown menu. Select “**Modified Morrow**” for equivalent strain equation. Enter 1 in the “**UnitCv**” box.

Now select the load tab. Enter the following information (refer to section 5.4 for more information on what each input is).

- In the **Spectrum** drop down box select “**ASCII Damage Source Assignment**”.
- Under **Hours per Sequence** enter 100.
- Under “**MAXRNG**” enter 30000.
- Under “**Scale**” enter 1
- Under “**Resd**” enter 0
- Under “**Dmg**” enter $1e-7$
- In the section containing the table with the title “**Stress Levels**”, there are two columns titled “**No.**” and “**Kn**”. In the first row under “**Kn**” enter the K_N of location 1 which is 2.5. In the next row enter the K_N of location 2 which is 5. You will note that the number next to the box titled “**Stress Levels**” has incremented to 2 indicating there are two cases to analyse.
- When selecting the spectrum file the user can choose to select the name and path using the “**Spectrum file**” button, see Figure 28. If the spectrum file has the same name and exists in the same directory as the input file then a path and name do not need to be specified. In this case just delete the default name “**cstamp**” and leave it blank; otherwise, click on “**Spectrum File**” to browse the file system and select the spectrum file.



Figure 28: Spectrum file input

Now select the Case Control tab and enter the following.

- Select **“serf_vs_passes”** and under the **“Number of Passes to Analyse”** dropdown menu select **“First Pass”**.
- Under the **“Material Data Output”** dropdown menu select **“Cyclic Stress-Strain”**. This option will output cyclic stress-strain data to the output file.
- Leave all other options as default.

After you have entered all the above data the Case Control tab should look like Figure 29.

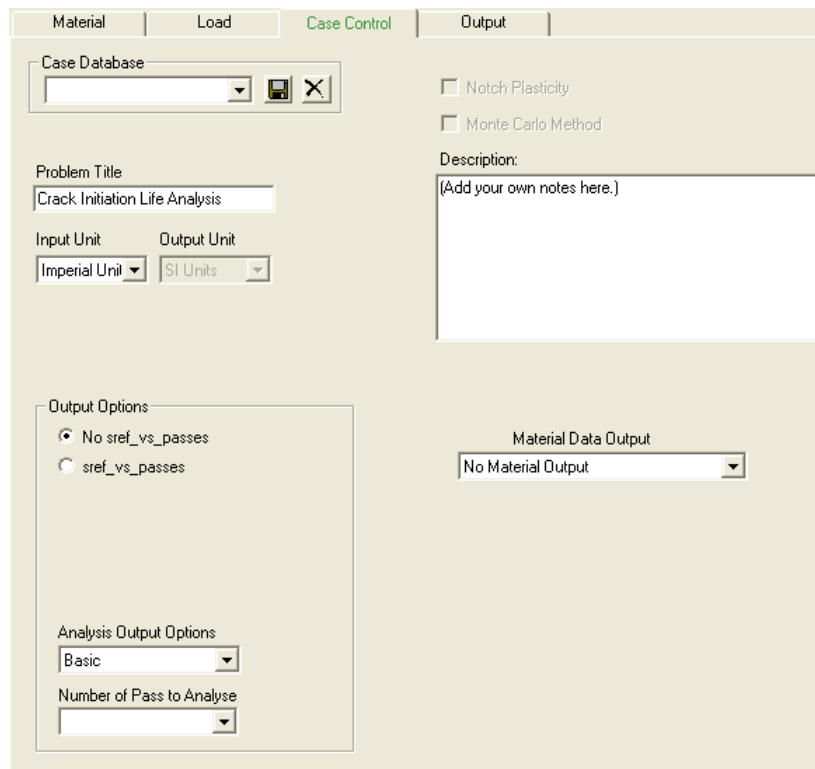


Figure 29: The Case Control tab

Now select **“File”** on the top menu and select **“Save As”**. Save the input file in the same location as the spectrum file and give it the same name as the spectrum file. Name the file **“Gen_seq.input”**, see Figure 30.

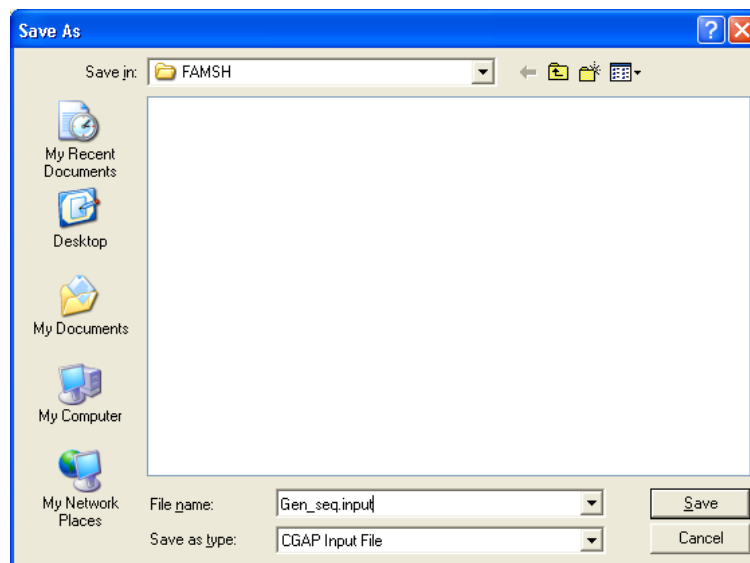


Figure 30: The save as dialog box

The input file looks similar to that presented in Table 18.

Table 18: The input file

Gen_seq.input
<pre>Crack Growth Analysis Program 1 -11 1 0 1 1 1 7050-T7351 2 1 0 2 2.5 5 1e-007 2 Flight Hours: 100. .</pre>

7.3 Execution

Once the files have been created, click on “**Build**” to build the case, see Figure 31.

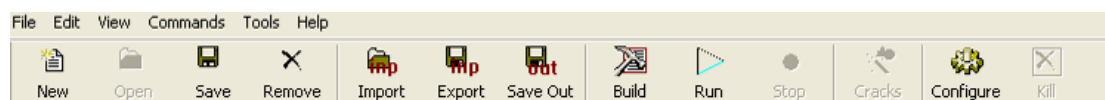


Figure 31: CGAP menu bar

You should see a new label underneath cases on the left hand of the screen, see Figure 32.

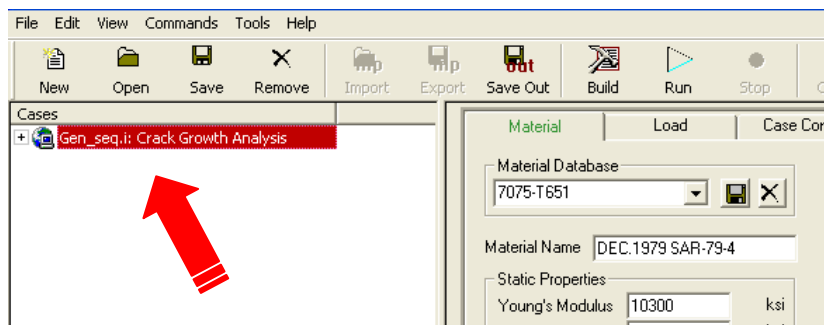


Figure 32: A new case underneath the cases control box

Multiple cases can be loaded into CGAP if need be.

After the problem has been successfully built, the final step is to execute the analysis by clicking on the “**Run**” button. After the analysis has been completed, the following message should be displayed in the message window, see Figure 33.

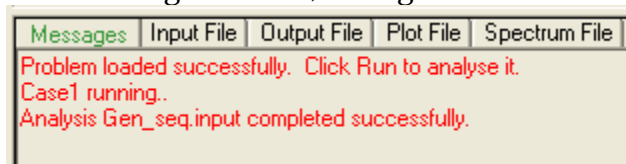


Figure 33: Messages returned after analysis

7.4 Results

After the analysis has been completed successfully several output files are created. These files are located in the same directory as the input file. The files created are:

Gen_seq.output
 Gen_seq.passes
 Gen_seq.dmo
 Gen_seq.dsout
 Gen_seq.truncspc

Gen_seq.passes contains the notch concentration factors and their associated fatigue life to failure measured in flight hours. For this example we expect that the output will return the values presented in Table 19.

Table 19: The estimated fatigue life at each notch feature using CGAP

Notch concentration factor	Estimated fatigue life (flight hours)
2.5	1,040,481
5	37,952

8. Discussion

Through the development and verification of the CGAP FAMSH module a series of test cases were developed. These cases were designed to test certain aspects of the CGAP FAMSH module. Some of these test cases have been included in Appendix E for the users benefit. A description of each case is provided in Table 28. These test cases were primarily used to verify the correct execution of the program. It should be noted that they are not a validation of the capability of FAMSH in predicting fatigue initiation lives. All test cases produced consistent results with those produced by the FAMSH executable.

It is important to consider the limitations with the current strain-life methodology. An understanding of the deficiencies and limitations will help the engineer to better interpret results in a more meaningful manner. Following is a discussion of some of these deficiencies and limitations.

8.1 Cyclic Stress-Strain Behaviour

Materials under cyclic loading can display various phenomena that are not as yet modelled in the current strain-life algorithm included in CGAP/FAMSH. The FAMSH module evaluates damage based on stabilised stress-strain hysteresis loops. But it is well known that this stabilised stress-strain behaviour observed under cyclic loading may be quite different to that observed under monotonic loading. Obviously this has significant implications in the application of the strain-life approach. For accurate estimates of strain it is important to use the correct stress-strain relationship. The difference in stress-strain behaviour between monotonic loading and cyclic loading clearly demonstrates a dependence on load history. This material dependence on the prior loading was first observed by Bauschinger [29] and is known as the Bauschinger effect. Bauschinger observed that the yield strength in tension or compression was reduced after the application of a load of opposite sign. The application of one single load is enough to change the stress-strain behaviour of a material. The way in which the behaviour changes after one single load is also affected by the temper of the material. A dramatic example of how the temper of a material can alter the stress-strain relationship with repeated loads has been presented by Morrow [30]. He observed the continuous stress-strain behaviour of copper for conditions where the copper was (a) fully annealed, (b) partially annealed and (c) cold worked. The results of this investigation are presented in Figure 34. For this particular material the curves eventually stabilise after enough repeated loads.

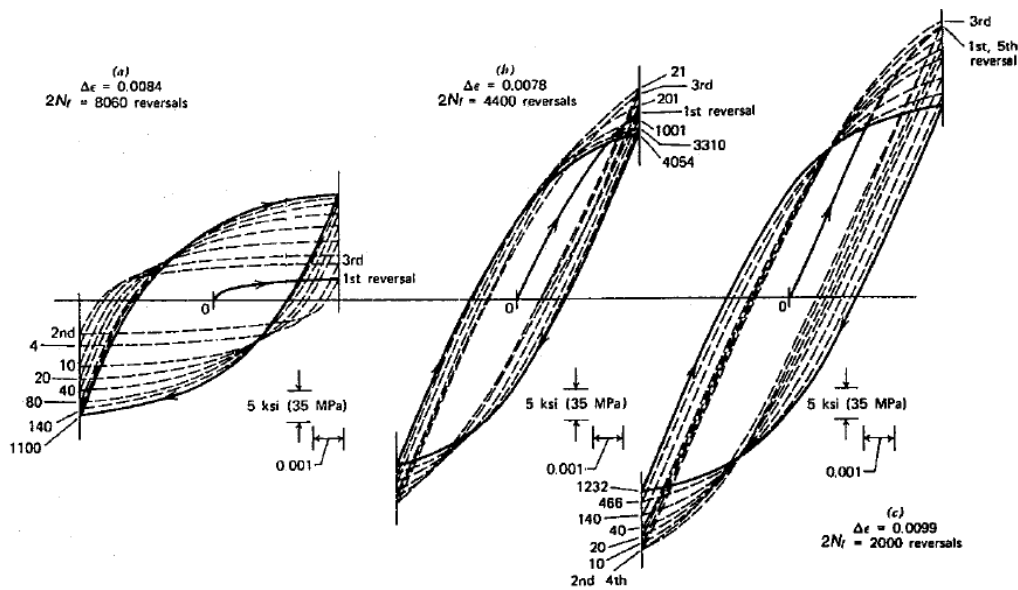


Figure 34: Stress-strain behaviour of copper subjected to cyclic strain-controlled axial loads. (a) Fully annealed, showing cyclic hardening. (b) Partially annealed, showing small cyclic hardening and softening. (c) Cold-worked, showing cyclic softening [30].

Other effects such as mean stress relaxation and ratchetting have also been observed with varying degrees in different materials. Some examples of the how these effects change the stress-strain response with repeated load applications are provided in Figure 35. Mean stress relaxation can be observed under strain-controlled cyclic loading where the mean stress of the spectrum relaxes towards zero, as observed in Figure 35 (a). When a non-symmetric constant amplitude load is applied under stress control another effect known as ratchetting may occur as in Figure 35 (b). At structural details such as notches, the local load is neither under strain control, nor under stress control, irrespective of the mode of control of the remote loading. Hence, we may expect to see a combination of mean stress relaxation and ratchetting as in Figure 35 (c).

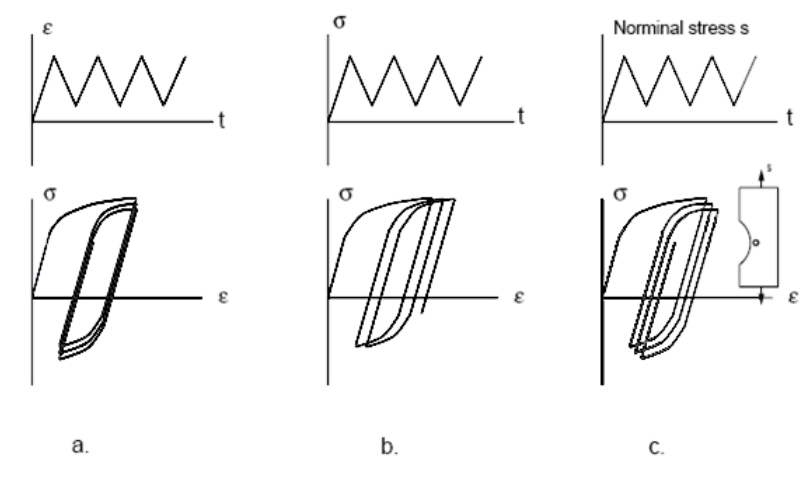


Figure 35: Elastic-plastic deformation behaviour subjected to (a) constant cyclic strains (b) constant cyclic stresses and (c) remote constant nominal cyclic stresses

In FAMSH, none of the above complex stress-strain behaviours are considered. Instead, the materials are assumed to be of Masing-type, *i.e.*, the hysteresis loops can be reconstructed by magnifying the steady-state cyclic stress-strain curve by a factor of two. The steady-state cyclic stress-strain curve is obtained by conducting tests on smooth (un-notched) specimens subjected to fully-reversed constant amplitude loading [31].

Other effects, such as cyclic softening and hardening, ratchetting etc which effect the shape of the hysteresis loops, have not as yet been considered in the code. These effects are hard too quantify in situations of variable amplitude loading and require a more sophisticated approach when modelling. The assumption used when applying the FAMSH code is that these second order effects have minimal impact on the final solution. However, it is up to the user to ensure the validity of these assumptions.

8.2 Notch Root Stress

FAMSH uses the Neuber method to estimate the stress at the root of a notch. The Neuber method, while assumed to be applicable to a wide range of geometries, does have limitations. The method does not hold true in situations where the notch root stress is not in phase with the remote load. It does not account for time dependant phenomenon such as creep and stress relaxation. It also does not account for cyclic stress relaxation at the notch root. While the Neuber method has limitations it is still widely used. In most cases the Neuber method slightly overestimates the notch-tip stresses and strains [32]. This may result in a conservative estimate of life. Other methods of estimating the notch root stress are available such as that by Glinka [33], which has been shown to provide better results in conditions of plane strain and torsional loading [34, 35]. The inclusion of other methods into CGAP to estimate the notch root stress could improve the accuracy of predictions for certain cases where the Neuber method has been shown to be deficient. At present the Neuber method is the only method available and it must be remembered that the method may lead to erroneous solutions in specific cases.

8.3 Definition and Validity of Material Data

Another important consideration when using the FAMSH code is the origin of the material data used in the analysis. This can be demonstrated by considering the input used to describe the strain-life curve. This curve can be generated in several ways and it is important to note on what basis these curves were created. A key consideration is the definition of failure. Failure could be considered to have occurred when the test specimen reaches a predefined level of compliance or when the specimen has completely failed. A change in the failure definition can completely change the interpretation of the solution. Another consideration is the surface condition of the test specimens used to generate the strain-life curve. Typically these tests are performed with smooth (un-notched) specimens, with certain amount of surface polishing, but the surface condition of the structure may not always match those of the specimens. Again this will affect interpretation of the results produced by FAMSH and the engineer must consider this when interpreting the results.

It is worth highlighting the strain-life techniques sensitivity to small strains where fatigue life estimates are high. To demonstrate this issue, consider two models both using the same

material, one using the equation description and the other using the tabular input. The models are identical and only differ in the way the notionally-identical material properties are entered into the program. After running the same problem using both the material inputs, the following output is produced, see Table 20.

Table 20: Total life predicted for various K_n values

K_n	Equation Input	Tabular Input	% Difference
3	153341.8	155716.2	-1.52%
3.5	77144.6	78133.6	-1.27%
4	40037.6	40235.6	-0.49%
4.5	21161.3	21903.5	-3.39%
5	13673.3	14215.3	-3.81%
5.5	9718.0	9004.4	7.92%
6	5632.5	5748.5	-2.02%
6.5	3786.7	3693.3	2.53%
7	2449.8	2321.4	5.53%

Although the inputs for the tabular definition match the equation definition exactly, the results in Table 20 indicate that errors introduced during interpolation have contributed to discrepancies in the final results. The associated sensitivity to input data particularly for small strains and long lives should be taken into consideration when interpreting strain-life results using this technique.

8.4 Damage Summation

The FAMSH code uses Miner's [25] rule to determine the level of damage. Miner's rule uses the linear accumulation concept proposed by Palmgren [26] as a measure of damage. This method of evaluating the amount of damaged incurred by each cycle does not account for load history effects. In other words, Miner's rule does not consider the effect the sequence of loads has on the accumulation of damage in a structure. Ignoring these effects can result in an order of magnitude difference in the final result [36, 37]. Improvements to the code could be implemented via the introduction of more sophisticated non-linear damage accumulation algorithms. A number of such models can be found in the literature [27].

9. Future Improvements

The following modifications to the FAMSH code are under consideration for future CGAP releases.

- The incorporation of a cyclic strain hardening model
- Ability to queue and run multiple jobs (similar to a batch file process)
- Additional and improved equivalent strain equations
- More advanced damage accumulation models to account for sequence effects
- The inclusion of other techniques to estimate the notch root stress
- Seamless interaction between strain-life and crack growth algorithms to provide total life estimates.
- Inclusion or emulation of other strain-life codes

Medium to long term research activities that may benefit from the CGAP analysis environment and improve the analysis capability include a study of the effect of net section size and surface condition on the fatigue limit. Improved damage models may help to disassociate the portion of damage due to crack growth and the component due to strain hardening of the material. This may lead to more robust material properties that may lead to a generalised predictive capability. More recent developments in fatigue life prediction have utilised the strain-life approach to predict crack growth directly [38-41]. Further research and development of this approach could be introduced to the CGAP environment and allow further evaluation of this technique.

10. Conclusion

This document summarises the important aspects of the strain-life theory and explains how this method is implemented into the CGAP environment using the strain-life module FAMSH. The document also provides the reader with guidance on and presents examples demonstrating the use of the new module.

The addition of the FAMSH strain-life algorithm into the CGAP tool set introduces consistent material data handling, built-in error checking, and a familiar graphical user interface, aiding quality management processes. These improvements will lead to improved robustness in the predictions which ultimately contributes to more efficient and reliable management of aircraft structural integrity.

11. Acknowledgements

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Appendix A: The Basis of the FAMSH Stress-Strain Relationship

In FAMSH, the following equation is used to relate the plastic stress and the plastic strain amplitude,

$$\sigma_p = \sigma_a - \sigma_{pl} = K' (\varepsilon_p)^{n'}, \quad \sigma_a > \sigma_{pl} \quad (27)$$

where σ_p is the plastic stress, σ_{pl} is the proportional limit, σ_a is the total applied stress and K' and n' are the cyclic strength coefficient and cyclic strain hardening coefficients respectively.

Using similar assumptions to that of the Ramberg-Osgood relation, we can express the total strain as the sum of the elastic and plastic components of strain such that:

$$\varepsilon_a = \varepsilon_e + \varepsilon_p \quad (28)$$

Rearranging equation 27, we get

$$\varepsilon_p = \left(\frac{1}{K'} (\sigma_a - \sigma_{pl}) \right)^{1/n'}, \quad \sigma_a > \sigma_{pl} \quad (29)$$

Therefore equation 28 becomes

$$\begin{aligned} \varepsilon_a = \varepsilon_e + \varepsilon_p &= \frac{\sigma_a}{E} + \left(\frac{1}{K'} (\sigma_a - \sigma_{pl}) \right)^{1/n'}, \quad \sigma_a > \sigma_{pl} \\ \varepsilon_a &= \frac{\sigma_a}{E} \quad \sigma_a \leq \sigma_{pl} \end{aligned} \quad (30)$$

Equation 30 can be used to represent the stabilised hysteresis loops of the stress-strain relation ship using a Masing type material approximation.

Appendix B: Deriving Material Parameters for the FAMSH Strain Life Equation

The strain-life equation used in FAMSH has a high degree of flexibility, however determining material parameters for this equation is not immediately apparent. This section provides a brief overview of one technique that can be used to determine the input parameters for the FAMSH strain-life equation. The method presented here is one method, but the reader is reminded that there maybe other better methods of evaluating these parameters.

For the purposes of this guide, we have chosen to use the tabulated data for 7050-T7351 from the CGAP material database. By using the terms PLET and ELET we can divide the strain-life curve into three sections, see Figure 36. The parameters PLET and ELET are determined by the user and the available tabulated data.

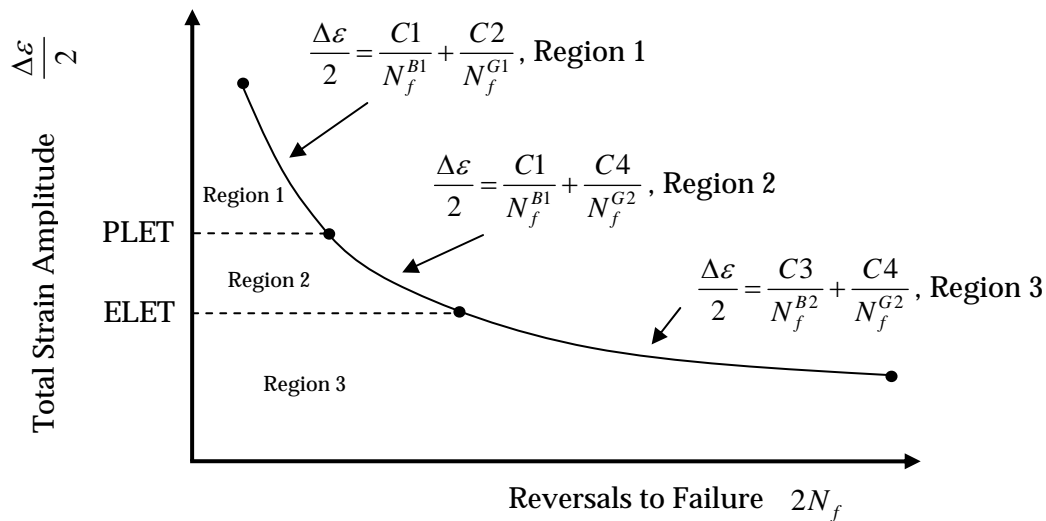


Figure 36: Strain-life curve representation in FAMSH

Using the tabulated data for the material 7075-T7351 we can create three data sets. The first data set contains all the data with a strain above PLET (that is all the data in Region 1). The second data set contains the data in Region 2 between PLET and ELET, and the third data set contains all the data with a strain below ELET (Region 3). After separating the 7075-T7351 data into these three sets, the tabulated data should look something like that in Table 21 depending on your choice of PLET and ELET.

Table 21: 7075-T7351 material data separated into three sets

Original Data Set		Data Set 1 (Region 1)		Data Set 2 (Region 2)		Data Set 3 (Region 3)	
Life	Strain	Life	Strain	Life	Strain	Life	Strain
10	0.085	10	0.085				
20	0.051	20	0.051				
30	0.039	30	0.039				
40	0.0325	40	0.0325				
60	0.025	60	0.025				
88	0.02	88	0.02				
145	0.0155	145	0.0155				
200	0.013	200	0.013				
350	0.0105	350	0.0105				
400	0.01			400	0.01		
500	0.0093			500	0.0093		
600	0.0087			600	0.0087		
700	0.0083			700	0.0083		
900	0.0078			900	0.0078		
1500	0.007			1500	0.007		
2000	0.0067			2000	0.0067		
3000	0.0063			3000	0.0063		
5000	0.0056					5000	0.0056
40000	0.0032					40000	0.0032
1000000	0.0015					1000000	0.0015

In this example $PLET = 0.0105$ and $ELET = 0.0063$. There are 8 other unknown parameters to be determined, and they are C1, C2, B1, G1, C3, C4, B2 and G2. Perhaps the easiest method to determine these parameters is to use a non-linear curve fitting program such as that contained in Origin[®] 6.0 [42].

If you use Origin[®] 6.0, you will need to create the function used in the fitting process. The inputs should look something like that shown in Figure 37.

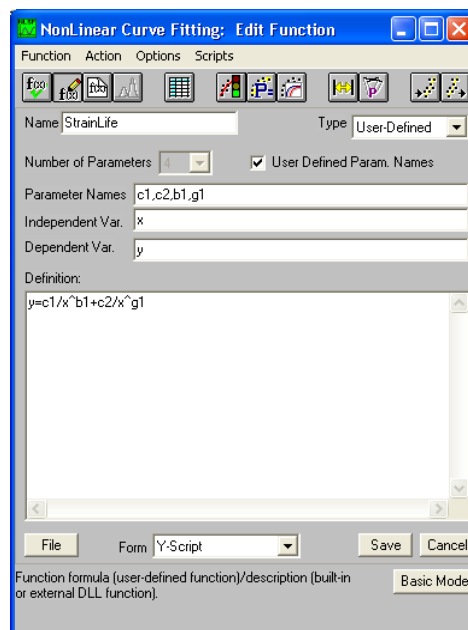


Figure 37: User defined non-linear curve fitting function

Using the non-linear curve fitting program determine the parameters C1, C4, B1 and G2 using the second data set. As we have chosen PLET to be greater than ELET, Region 2 is defined with the parameters C1, C4, B1 and G2 (If PLET was less than ELET then Region 2 would be defined with C2,C3, G1 and B2). The fit should look something like that shown in Figure 38.

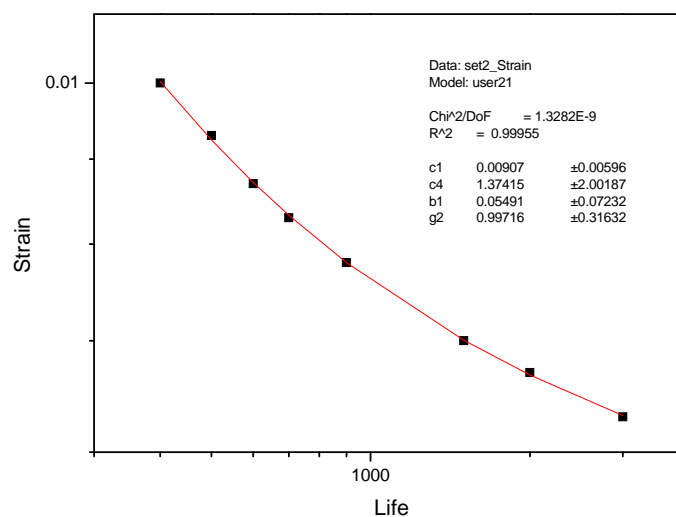


Figure 38: Curve fit for data set 2 using Origin[®] 6.0

When interpreting the results of the non-linear curve fit it is necessary to identify the terms relating to the elastic strain and the plastic strain. Remember that the strain-life equation (equation 12) is the sum of the plastic and elastic components of strain. The plastic component of the equation is identified by the larger gradient on a log-log plot. Thus the larger of the two exponents in equation 12 identifies the plastic component.

By fitting Region 2 first we now have values for C1, C4, B1 and G2 which we can use in determining the parameters in the other regions. Now using the first data set, input C1 and B1 as fixed parameters and use the non-linear curve fitting algorithm to find C2 and G1. The result of the fitting should look like that shown in Figure 39.

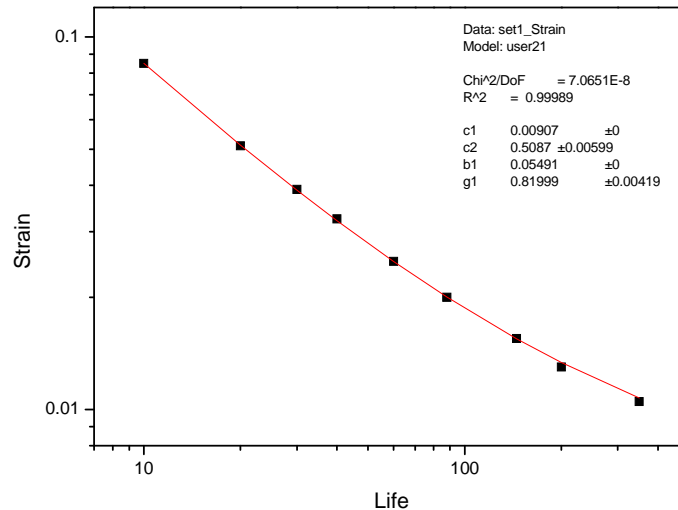


Figure 39: Curve fit for data set 1 using Origin® 6.0

Similarly we now use C4 and G2 (determined from our non-linear curve fit of Region2) as fixed parameters to determine the final two unknown parameters C3 and B2 using data set 3. The curve fit is presented in Figure 40.

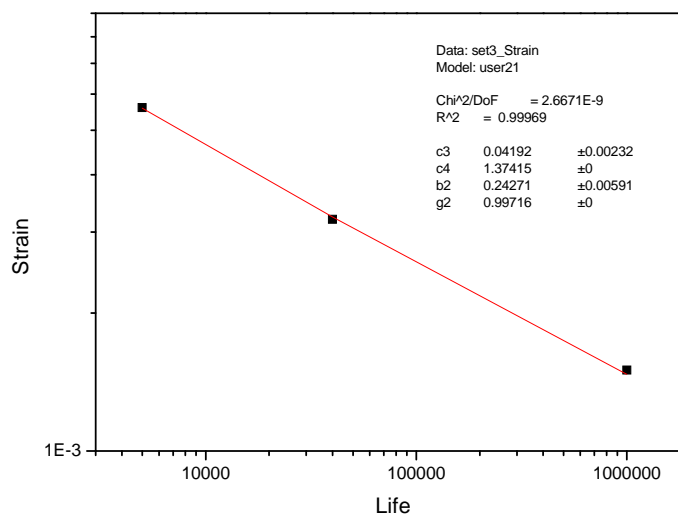


Figure 40: Curve fit for data set 3 using Origin® 6.0

After fitting the final set of data, we now have determined all the parameters needed to define the strain-life equation. These parameters are presented in Table 22.

Table 22: Fitting parameters for the FAMSH strain-life equation for 7075-T7351 aluminium

Parameter	Region 2							
	Region 1				Region 3			
	<i>C2</i>	<i>G1</i>	<i>C1</i>	<i>B1</i>	<i>C4</i>	<i>G2</i>	<i>C3</i>	<i>B2</i>
Value	0.5087	0.81999	0.00907	0.05491	1.37415	0.99716	0.04192	0.24271

In this example when compared to the original 7075-T7351 aluminium data, the FAMSH strain-life equation produces excellent agreement, see Figure 41.

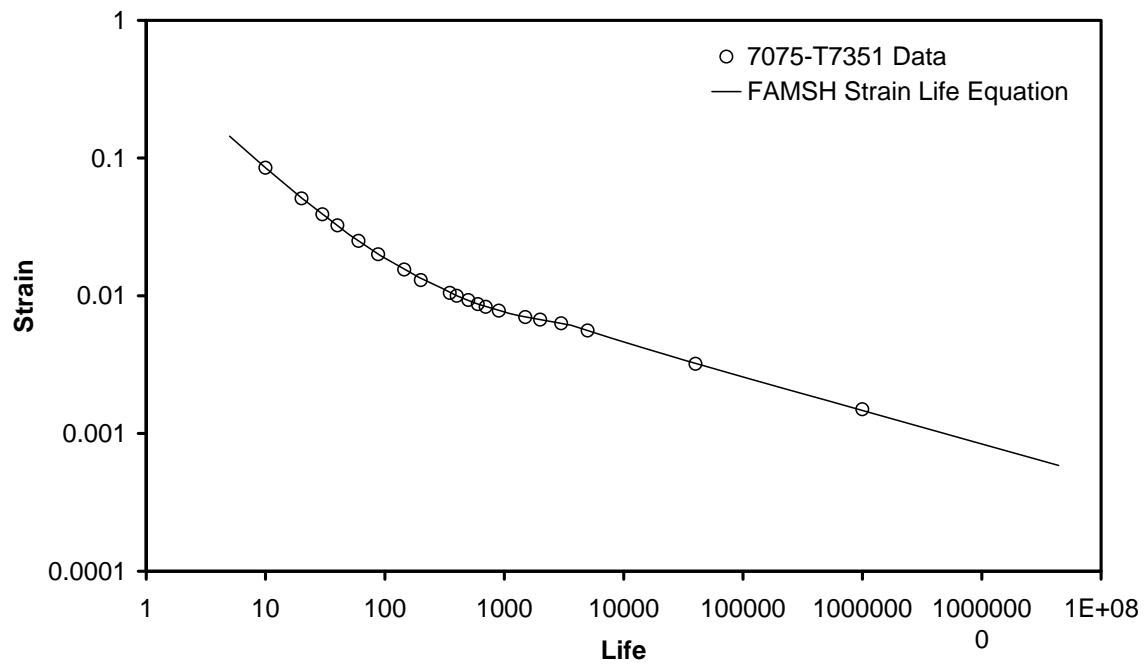


Figure 41: The FAMSH strain-life equation compared to the original 7075-T7351 aluminium data

Appendix C: FAMSH Output Files

Table 23: An example of the filename.dmo file

Example.dmo				
FAMSH PROGRAM INITIATED 20090731 10:45:06				
Title: generic test seq				
LOADS APPLICATION NUMBER TWO				
KN = 1.0000 SREF = 2.500 (KN*SREF) = 2.500				
DAMAGE DISTRIBUTION BY MISSION				
MISSION NUMBER	MISSION UTILIZ.	TOTAL DAMAGE	AVG DMG PER FLT. DMG	% MISSION OF TOTAL
1	121	0.1345E-02	0.1111E-04	0.88
2	65	0.1545E-02	0.2377E-04	1.01
3	63	0.2486E-02	0.3946E-04	1.63
4	132	0.1991E-02	0.1508E-04	1.30
5	94	0.2596E-02	0.2762E-04	1.70
6	139	0.6220E-02	0.4475E-04	4.07
7	75	0.1867E-02	0.2489E-04	1.22
8	193	0.5910E-02	0.3062E-04	3.87
9	96	0.3295E-02	0.3433E-04	2.16
10	95	0.2777E-02	0.2923E-04	1.82
11	114	0.4070E-02	0.3570E-04	2.66
12	33	0.6235E-03	0.1889E-04	0.41
13	91	0.3849E-02	0.4230E-04	2.52
14	126	0.4775E-02	0.3789E-04	3.12
15	111	0.2781E-02	0.2505E-04	1.82
16	175	0.6870E-02	0.3926E-04	4.49
17	216	0.1363E-01	0.6309E-04	8.91
18	206	0.1511E-01	0.7336E-04	9.88
19	77	0.9120E-02	0.1184E-03	5.96
20	102	0.4437E-02	0.4350E-04	2.90
21	66	0.4884E-02	0.7399E-04	3.19
22	82	0.5841E-02	0.7124E-04	3.82
23	153	0.1823E-02	0.1192E-04	1.19
24	107	0.2016E-02	0.1884E-04	1.32
25	87	0.1791E-02	0.2059E-04	1.17
26	90	0.2324E-02	0.2582E-04	1.52
27	120	0.3334E-02	0.2778E-04	2.18
28	109	0.4402E-02	0.4038E-04	2.88
29	102	0.4158E-02	0.4077E-04	2.72
30	191	0.3698E-02	0.1936E-04	2.42
31	143	0.1063E-02	0.7436E-05	0.70
32	94	0.1027E-02	0.1093E-04	0.67
33	290	0.2573E-02	0.8874E-05	1.68
34	150	0.5210E-02	0.3473E-04	3.41
35	127	0.1492E-02	0.1175E-04	0.98
36	100	0.1847E-02	0.1847E-04	1.21
37	55	0.9397E-02	0.1709E-03	6.15
38	11	0.7360E-03	0.6691E-04	0.48
TOTAL	4401	0.1529	0.3475E-04	100.0

Table 24: An example of the damage density information contained in the filename.dsout file

Example.dsout				
FAMSH PROGRAM INITIATED 20090604				
Title: generic test seq				
LOADS APPLICATION NUMBER TWO				
KN = 1.0000 SREF = 2.500 (KN*SREF) = 2.500				
BIN #	RANGE (%)	OCCURRENCES IN RANGE	PCT DMG	OCCURRENCES REMAINING
1	0 - 5	14.5	0.0	441.5
2	5 - 10	54.0	1.7	387.5
3	10 - 15	347.0	41.6	40.5
4	15 - 20	34.0	22.8	6.5
5	20 - 25	4.5	5.6	2.0
6	25 - 30	0.5	1.8	1.5
7	30 - 35	0.0	0.0	1.5
8	35 - 40	0.0	0.0	1.5
9	40 - 45	0.5	7.3	1.0
10	45 - 50	1.0	19.1	0.0
11	50 - 55	0.0	0.0	0.0
12	55 - 60	0.0	0.0	0.0
13	60 - 65	0.0	0.0	0.0
14	65 - 70	0.0	0.0	0.0
15	70 - 75	0.0	0.0	0.0
16	75 - 80	0.0	0.0	0.0
17	80 - 85	0.0	0.0	0.0
18	85 - 90	0.0	0.0	0.0
19	90 - 95	0.0	0.0	0.0
20	95 - 100	0.0	0.0	0.0
21	100	0.0	0.0	0.0
TOTAL CYCLES			456.0	
TOTAL DAMAGE			1.22661E-04	
MAXIMUM DELTA STRESS:			60000.00	

Table 25: An example of the filename.passes file

Example.passes	
C:\Cgap\Example 1\Example.	
Flight Hours	Kn
8152.52148437500	2.500000
313.114379882812	5.000000

Table 26: An example of the filename.truncspc file

Example.truncspc							
2	1	CYCLE					
0	1.000	CYCLE COUNT & FLIGHT DURATION					
4391	38	FLIGHT NUMBER & MISSION TYPE					
224	1.000	CYCLE COUNT & FLIGHT DURATION					
0	0.00	38001022	1.00	38001022	-13408.00	38002023	-1773.00
38002023	-9068.00	38003019	6891.00	38003019	1087.00	38004004	15104.00
38004004	5740.00	38004005	13942.00	38004005	10422.00	38004004	13439.00
38004004	7405.00	38005004	13167.00	38005004	7246.00	38007008	13512.00
38007008	10301.00	38007007	14201.00	38007007	6401.00	38007007	14201.00
38007007	6401.00	38007007	13380.00	38007007	7222.00	38007007	13380.00
38007007	7222.00	38007007	13380.00	38007007	7222.00	38007007	14714.00
.							
.							
.							

Table 27: An example of the filename.output file

Example.output					
<pre> *** FAMSH Version 1.42 - Modified FAMS FAMS PROGRAM INITIATED 20090714 13:24:17 * * * * Information * * * * Passes vs Kn data are appended to file C:\Program files\DSTO\CGAP\Analysis Files\Example.passes ***** Information ***** Default (Morrow) equation selected. ***** ***** FATIGUE ANALYSIS OF METALLIC STRUCTURES (F A M S) Developed by N.R.Krishnan Modified by K.N.Bailey ***** MATERIAL DATA Material D7075-T651 AL ALLOY (DSTO Trendline) Young's Modulus (psi) 1.0300E+07 Yield Stress (psi) 68000. Ultimate Stress (psi) 82500. Fracture Stress (psi) 110000. Title: generic test seq LOADS APPLICATION NUMBER TWO KN = 1.0000 SREF = 2.500 (KN*SREF) = 2.500 name 2 TIME REPRESENTED BY LOADING FOR BLOCK NO. 1 IS 1.000 NOTCH STRESSES AND STRAINS COMPUTED FOR 458 UNIQUE LEVELS BLOCK DAMAGE = 6.78602E-05 name 2 TIME REPRESENTED BY LOADING FOR BLOCK NO. 2 IS 1.000 NOTCH STRESSES AND STRAINS COMPUTED FOR 456 UNIQUE LEVELS BLOCK DAMAGE = 5.48013E-05 TOTAL DAMAGE = 1.22661E-04 LIFE = 16305.0 NUMBER PASSES = 8152.5215 APPLIED MAXIMUM LOAD = 16952.00 MINIMUM LOAD = -13408.00 NUMBER OF BLOCKS <FLIGHTS> ANALYZED = 2 LOADS APPLICATION NUMBER TWO name 2 NOTCH STRESSES AND STRAINS COMPUTED FOR 458 UNIQUE LEVELS BLOCK DAMAGE = 6.78602E-05 name 2 NOTCH STRESSES AND STRAINS COMPUTED FOR 456 UNIQUE LEVELS BLOCK DAMAGE = 5.48013E-05 TOTAL DAMAGE = 1.22661E-04 LIFE = 16305.0 NUMBER PASSES = 8152.5215 LIFE UNDER LOAD BLOCKS REPEATED = 16305.0 NUMBER PASSES = 8152.5215 The option was chosen to use LOADS APPLICATION NUMBER TWO for damage and truncation studies. TRUNCATION % OF ORIGINAL CYCLES CYCLES % CUTOFF DAMAGE REMOVED REMAINING REMOVED 1.00E-08 0.00012 100.00 30.00 426.00 6.579 1.00E-07 0.00011 89.38 192.00 264.00 42.105 1.00E-06 0.00005 39.07 442.00 14.00 96.930 1.00E-05 0.00004 28.54 451.00 5.00 98.904 1.00E-04 0.00004 28.54 451.00 5.00 98.904 1.00E-03 0.00004 28.54 451.00 5.00 98.904 1.00E-02 0.00004 28.54 451.00 5.00 98.904 1.00E-01 0.00004 28.54 451.00 5.00 98.904 1.00E-07 0.00011 89.38 192.00 264.00 42.105 TOTAL # CYCLES 456.00 TOTAL # REAL CYCLES : 455.00 TOTAL # VIRTUAL CYCLES 'RAINFLOW': 1.00 TOTAL # CYCLES : 456.00 </pre>					

```

RESIDUAL STRESS AT END OF LOADING =      0.00
LAST LOAD CAUSING YIELD           =      0.00

Title: generic test seq
LOADS APPLICATION NUMBER TWO
KN = 1.0000      SREF = 5.000      (KN*SREF) = 5.000

      name 2
      TIME REPRESENTED BY LOADING FOR BLOCK NO. 1 IS      1.000
      NOTCH STRESSES AND STRAINS COMPUTED FOR      458  UNIQUE LEVELS
      BLOCK DAMAGE = 1.87001E-03

      name 2
      TIME REPRESENTED BY LOADING FOR BLOCK NO. 2 IS      1.000
      NOTCH STRESSES AND STRAINS COMPUTED FOR      456  UNIQUE LEVELS
      BLOCK DAMAGE = 1.51884E-03
TOTAL DAMAGE = 3.38886E-03      LIFE = 590.169      NUMBER PASSES = 295.0847
APPLIED MAXIMUM LOAD = 16952.00      MINIMUM LOAD = -13408.00
NUMBER OF BLOCKS <FLIGHTS> ANALYZED = 2

LOADS APPLICATION NUMBER TWO

      name 2
      NOTCH STRESSES AND STRAINS COMPUTED FOR      458  UNIQUE LEVELS
      BLOCK DAMAGE = 1.68650E-03

      name 2
      NOTCH STRESSES AND STRAINS COMPUTED FOR      456  UNIQUE LEVELS
      BLOCK DAMAGE = 1.50659E-03
TOTAL DAMAGE = 3.19310E-03      LIFE = 626.351      NUMBER PASSES = 313.1757
LIFE UNDER LOAD BLOCKS REPEATED = 626.229      NUMBER PASSES = 313.1144
The option was chosen to use LOADS APPLICATION NUMBER TWO for damage and truncation studies.

TRUNCATION
CUTOFF      DAMAGE      % OF ORIGINAL      CYCLES      CYCLES      %
      DAMAGE      DAMAGE      REMOVED      REMAINING      REMOVED
1.00E-08      0.00319      100.00      10.00      446.00      2.193
1.00E-07      0.00319      100.00      10.00      446.00      2.193
1.00E-06      0.00318      99.68      29.00      427.00      6.360
1.00E-05      0.00169      52.91      394.00      62.00      86.404
1.00E-04      0.00039      12.11      451.00      5.00      98.904
1.00E-03      0.00039      12.11      451.00      5.00      98.904
1.00E-02      0.00039      12.11      451.00      5.00      98.904
1.00E-01      0.00039      12.11      451.00      5.00      98.904

1.00E-07      0.00319      100.00      10.00      446.00      2.193
TOTAL # CYCLES      456.00
TOTAL # REAL CYCLES      :      455.00
TOTAL # VIRTUAL CYCLES 'RAINFLOW':      1.00
TOTAL # CYCLES      :      456.00
RESIDUAL STRESS AT END OF LOADING = -3561.05
LAST LOAD CAUSING YIELD           = 16952.00

Analysis completed successfully.
.
.
.

```

Appendix D: Sample FAMSH Materials Files

Sample *flmat1.dat* file

```
>D7075-T651    AL ALLOY (DSTO Trendline)
10300    68    82.5    110
32    1000    1
0.0058732    60.494
0.0063586    65.493
0.0068504    70.427
0.0074646    74.137
0.0082181    76.542
0.0090608    78.314
0.0099697    79.743
0.010935    80.959
0.0119517    82.031
0.013017    82.999
0.0141289    83.886
0.0152862    84.711
0.0164878    85.485
0.0177327    86.216
0.0190204    86.911
0.0203503    87.576
0.0217217    88.214
0.0231342    88.828
0.0245875    89.421
0.0260812    89.996
0.0276152    90.554
0.0291896    91.096
0.0308049    91.625
0.0324628    92.142
0.0341662    92.649
0.0359213    93.149
0.0377396    93.644
0.0396416    94.141
0.0416642    94.646
0.0438716    95.176
0.053135    97.179
0.0654031    99.435
20
0.018    602
0.013    1100
0.012    1340
0.0085    2980
0.008    3640
0.0075    4450
0.007    6000
0.0065    7330
0.006    9900
0.0055    12100
0.005    14800
0.0045    22000
0.004    32900
0.0035    54200
0.003    109000
0.0025    243000
0.002    540000
```

Sample *flmat2.dat* file

```
>7075-T651    DEC.1979 SAR-79-4
10300    68    82.5    110    1.31575e-005    3.27
0.01103    0.3221    0.0035    2.56
0.0588    0.1573    0.7444    3.1484    0.01151    0.009454
```


Appendix E: FAMSH Test Cases

To verify the FAMSH module, a number of test cases were developed. Some of the test cases have been included here. All the test cases were evaluated using the original FAMSH code and compared to the results produced by CGAP. All cases returned consistent results. Note: These models are only to be used for validation and not for any other purposes. Material data and parameters should not be transferred to solve real engineering problems.

The attached CDROM contains all the CGAP strain life module validation cases.

Table 28: FAMSH Test Case descriptions

Case No.	Test Description
1	Uses a moderate sized spectrum file in conjunction with two reference stress values
2	This case, similar to the first, uses a smaller version of the same spectrum file this time only containing 2 flights
3	This case uses four reference stresses and is designed to fail on the last reference stress analysed
4	A spectrum file containing 2 flights is defined in block format using DSA
5	A spectrum file containing 1 flight is defined in block format using DSA
6	A spectrum file containing 1 flight is defined in cycle format using DSA
7	A spectrum file containing 1 flight is defined in cycle format with no DSA
8	A spectrum file containing 2 flights is defined in cycle format with no DSA
9	A spectrum file containing 1 flight is defined in block format with no DSA
10	A spectrum file containing 2 flights is defined in block format with no DSA
11	A large spectrum file is used
12	An equation material description is used (7075-T651) with the case 1 spectrum
13	Removed the Flight hours and maximum delta stress option from the input file
14	No stress-strain information is output and Basic analysis output is requested
15	Cyclic stress-strain information is output and Basic analysis output is requested
16	hysteresis stress versus hysteresis stress-strain information is output and Basic analysis output is requested
17	No stress-strain information is output and detailed analysis output is requested
18	No stress-strain information is output and more detailed analysis output is requested
19	No stress-strain information is output and most detailed analysis output is requested
20	Residual stress is added to the analysis
21	One pass is used in the analysis
22	A Kn of 1.5 is used in conjunction with the reference stresses
23	A conversion factor of 1.2 is used in the analysis
24	The loopin equivalent strain equation is requested
25	The modified loopin equivalent strain equation is requested
26	The Walker equivalent strain equation is requested
27	The Smith-Watson-Topper equivalent strain equation is requested
28	The F-18 equivalent strain equation is requested

Table 29: FAMESH Test Case Inputs

Case No.	IPT1	IPT2	IPT3	IPT4	IPT5	Kn	Material	MATF	UNIT	CV	RS	NMLT	SREF	DCUT	ESE	m	α	β	γ	Flight Hours	DSA	CYCLE/BLOCK	Multiple/Single Flight
1	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
2	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
3	1	12	1	0	0	1	D7075-T651	1	1	0	4	2.5	5	1 10	1.E-07	2				15000	YES	CYCLE	Multiple
4	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	BLOCK	Single
5	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	BLOCK	Multiple
6	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Single
7	1	12	1	1	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	NO	CYCLE	Single
8	1	12	1	1	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	NO	CYCLE	Multiple
9	1	12	1	1	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	NO	BLOCK	Single
10	1	12	1	1	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	NO	BLOCK	Multiple
11	0	-11	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
12	1	10	1	0	0	1	7075-T651	2	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
13	1	11	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					1	YES	CYCLE	Multiple
14	0	-11	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
15	1	-11	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
16	2	-11	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
17	0	10	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
18	0	11	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
19	0	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
20	1	12	1	0	0	1	D7075-T651	1	1	20000	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
21	1	12	1	0	1	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
22	1	12	1	0	0	1.5	D7075-T651	1	1	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
23	1	12	1	0	0	1	D7075-T651	1	1.2	0	2	2.5	5	1.E-07	2					15000	YES	CYCLE	Multiple
24	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	3			0.54		15000	YES	CYCLE	Multiple
25	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	4		0.5	0.6		15000	YES	CYCLE	Multiple
26	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	5	0.41				15000	YES	CYCLE	Multiple
27	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	6	0.5				15000	YES	CYCLE	Multiple
28	1	12	1	0	0	1	D7075-T651	1	1	0	2	2.5	5	1.E-07	7			0.432	12900	15000	YES	CYCLE	Multiple

Table 30: FAMESH Test Case Fatigue Life Estimates

Case	Kn	CGAP1.8 (FAMESH)	FAMESH 1.50 LINUX	% difference
1	2.5	98082.37	98082.37	0.00%
	5.0	6341.44	6341.44	0.00%
2	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
3	2.5	28781.00	28781.00	0.00%
	5.0	1860.58	1860.58	0.00%
	1	2145999.00	2145999.00	0.00%
	10	Notch Strain Exceeds Fracture Strain For Material		
4	2.5	233007031.05	233007031.05	0.00%
	5.0	7181150.94	7181150.94	0.00%
5	2.5	115019049.25	115019049.25	0.00%
	5.0	3946915.39	3946915.39	0.00%
6	2.5	221042834.00	221042834.00	0.00%
	5.0	8424547.69	8424547.69	0.00%
7	2.5	221042834.00	221042834.00	0.00%
	5.0	8424547.69	8424547.69	0.00%
8	2.5	221042834.00	221042834.00	0.00%
	5.0	8424547.69	8424547.69	0.00%
9	2.5	233007031.05	233007031.05	0.00%
	5.0	7181150.94	7181150.94	0.00%
10	2.5	115019049.25	115019049.25	0.00%
	5.0	3946915.39	3946915.39	0.00%
11	2.5	249151.21	249151.21	0.00%
	5.0	10864.74	10864.74	0.00%
12	2.5	220312.25	220312.25	0.00%
	5.0	3457.82	3457.82	0.00%
13	2.5	6.54	6.54	0.00%
	5.0	0.42	0.42	0.00%
14	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
15	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%

Case	Kn	CGAP1.8 (FAMSH)	FAMSH 1.50 LINUX	% difference
16	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
17	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
18	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
19	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
20	2.5	48337584.70	48337584.70	0.00%
	5.0	4563759.61	4563759.61	0.00%
21	2.5	122287885.33	122287885.33	0.00%
	5.0	4696715.79	4696715.79	0.00%
22	2.5	40333647.35	40333647.35	0.00%
	5.0	2148989.19	2148989.19	0.00%
23	2.5	316442565.90	316442565.90	0.00%
	5.0	10173569.74	10173569.74	0.00%
24	2.5	28051631.66	28051631.66	0.00%
	5.0	2624609.12	2624609.12	0.00%
25	2.5	22761393.09	22761393.09	0.00%
	5.0	2007716.34	2007716.34	0.00%
26	2.5	32232623256.35	32232623256.35	0.00%
	5.0	968792708.66	968792708.66	0.00%
27	2.5	32672040.32	32672040.32	0.00%
	5.0	3145626.73	3145626.73	0.00%
28	2.5	16197755.53	16197755.53	0.00%
	5.0	2563178.05	2563178.05	0.00%

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19. ABSTRACT Existing airworthiness standards require that all aspects of fatigue be considered in the design, development and maintenance of aircraft structures. To minimise costs and improve combat readiness requires accurate and efficient fatigue life evaluation. This report details the introduction of a strain-life algorithm known as FAMSH into the software tool suite known as CGAP developed and maintained at the DSTO. Along with improvements to the original FAMSH code this most recent development introduces a materials database and dynamic memory allocation. With other additional improvements the latest release of the CGAP environment seeks to improve the ease with which the engineer is able to accurately and reliably conduct fatigue life analysis. Contained within this report is an explanation of the strain-life theory in conjunction with a detailed description of its implementation in the CGAP GUI environment. Examples are provided to guide the user through its operation.							